A SURVEY OF ASTRONOMY

Edited by COLIN A. RONAN
Associate Editor PATRICK MOORE

There are already many excellent books upon elementary astronomy, and many technical works aimed purely at the expert. Books which form a connecting link between these two standards are rare. In general, the student finds that he has to pass straight from a very elementary volume on to a work which is of a high standard technically, and includes copious mathematical formulae.

The aim of the present series is to fill this gap in the literature. Some elementary knowledge has been assumed, but the general reader with no specialized knowledge will be able to follow the text, since mathematical formulae have been used sparingly and, in general, in footnotes or appendices. Some volumes necessarily make more use of mathematics than others, but the reader is always taken step by step and even those without mathematical knowledge will still be able to follow the argument.

Each book has been written by an expert in his specific field, and should be regarded as a 'step' from the elementary to the technical field. Once this series of books has been read and digested, the student should be ready to proceed to more technical volumes. Each volume is complete in itself although, of course, the *Survey* will only be complete within the series as a whole.

The series is, then, designed for the benefit of the serious amateur and for the student. It is hoped that University students who are considering taking science degrees will find the books particularly useful.

Throughout the series the design of the volumes has been to give an up-to-date picture, indicating both present advances and also present limitations to our knowledge.

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Solar Research

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A SURVEY OF ASTRONOMY: 4

Solar Research

GIORGIO
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A Survey of Astronomy

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The corona, photographed by Van Biesbroeck on 25th February 1952

SOLAR RESEARCH

by Giorgio Abetti

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Chapter I

THE SUN AMONG THE STARS

The Sun is only one of the multitudes of stars which throng the sky, but all the others are so much farther away from the Earth that they appear as mere points of light. The Sun, however, is of considerable apparent size, having an angular diameter which varies between 32′ 36″ at perihelion in January to 31′ 32″ at aphelion in July.

It is therefore natural that we should first try to establish the relationship of the Sun to the system of which it is a part – that is to say, the Milky Way or Galaxy – and also its movements and its physical characteristics as compared with the other stars.

Because of the great amount of light which we receive from the Sun, it is relatively easy to study its spectrum. Investigations have shown that certain other stars yield similar spectra, and it may therefore be supposed that our Sun may be included in this general classification, which forms part of a definite series representing a stage in stellar evolution.

By investigating the numbers, movements and distribution of the stars, including the faintest which are detectable with the most powerful telescopes available today, it may be shown that the whole Solar System is only a part of an even larger system, the Galaxy or Milky Way. This has led on to the study of the 'extragalactic nebulae', more suitably termed 'external galaxies', many of which are similar in size and shape to our Milky Way. Examination of these extragalactic nebulae shows that there is a pattern of evolution amongst

them, and during this evolution the birth and death of stars is also taking place.

It has been found that the Milky Way is spiral in structure, with arms extending from its nucleus. The centre of the system lies in the direction of the Sagittarius star-clouds. The total diameter of the spiral has been estimated as 100,000 light-years, while the thickness of the nucleus is about 10,000 light-years. Between the spiral arms, and indeed spread all among the stars, is a considerable quantity of interstellar material. If luminous, this material seems to blend with the stars themselves, and we see the so-called 'irregular nebulae' such as that in Orion. Elsewhere we find obscured areas called 'dark nebulae', which consist mainly of hydrogen.

The Sun is one of tens of thousands of stars which make up the Milky Way. It lies roughly on the equatorial plane of the system, but is not close to the centre, and lies at a distance of approximately 30,000 light-years from the nucleus. Various methods of research have shown that the Galaxy is rotating rapidly around its centre – not in the manner of a solid body such as a wheel, but obeying Kepler's laws, as in the case of the planets in the Solar System. Thus, because of this differential rotation, the more distant parts of the Galaxy lag behind with respect to the nearer parts. The Sun, in its position well away from the nucleus, is moving with a velocity of 285 km/sec toward a point in the constellation of Cygnus; one complete rotation of the Sun and its planets around the centre of the Galaxy takes about 250 million years. Because of this rotation, it has been shown that the Sun is moving in relation to the brighter and nearer stars with a velocity of 19 km/sec in the direction of a point located in the constellation of Hercules.

Let us postpone a detailed description of the solar spectrum, and consider the Sun's relationship to the other stars in the Milky Way – and, of course, in the external galaxies.

Even a cursory examination of the stars with the naked eye shows them to be of different colours; as with all bodies which emit light, these colours give indications of differences in surface temperature. In general, the Sun and stars emit a continuous band of colours or a 'continuous spectrum', but a closer examination of such spectra reveals the presence in them of absorption lines.* Such lines were first recorded in 1802 by Wollaston and discovered independently in 1814 by Fraunhofer, after whom they are named. In spite of the presence of Fraunhofer lines the continuous spectrum indicates that the Sun and stars are almost perfect radiators at all wavelengths. To some extent, therefore, it becomes possible to apply the laws relating to black bodies, and to deduce the surface temperatures of the stars.

Basing his work on the colours and spectra, Father Angelo Secchi made the first spectral classification of stars into four types, in order of descending temperature. Later, more complex classifications were introduced, using the same basic parameter. The classification in use today is that of the *Draper Catalogue*, named in honour of Henry Draper of the Harvard College Observatory; it is by no means perfect, but is being steadily improved as new information comes to hand. In this system, the various categories are denoted by letters of the alphabet, but the general order of the alphabet is disregarded, and the classes are lettered O, B, A, F, G, K and M. Stars in groups O to A are blue-white in colour, those from F to K yellow, and K to M red.

Briefly, it may be said that class O comprises a limited number of stars with a luminosity up to 10,000 times that of the Sun, and with masses up to 50 times greater than the Sun's. Their surface temperatures are estimated as being between 20,000 and 40,000 degrees. An O-type star shows a

* A full discussion of the nature of spectral lines is to be found in *Astronomical Spectroscopy* by A. D. Thackeray, also in this series.

continuous spectrum with absorption lines identified as due to helium (He), carbon (C), oxygen (O), nitrogen (N), and silicon (Si), up to four or five degrees of ionization. Spectra of B-type stars are still very intense in the violet, and the surface temperatures range from 10,000 to 20,000 degrees; the masses and luminosities are appreciably greater, and absorption lines are present for oxygen, nitrogen and neutral helium. Lines for the Balmer series of hydrogen increase in intensity as one progresses from B to A, with 'enhanced lines' of the elements Si, C, O and magnesium (Mg). Among the brighter stars of this group are Rigel, Spica and Regulus.

In A-type spectra, the Balmer series of hydrogen lines is dominant. Lines due to metals in a simple state of ionization (calcium, magnesium, iron) are also found. The surface temperatures are between 7000 and 10,000 degrees. Typical of this class are Sirius, Vega, Deneb and Castor. Stars of class F have temperatures of 6000 to 7000 degrees, and are less intense in the violet region; hydrogen lines are present, and there are also lines due to neutral atoms. Particularly noticeable are the lines of calcium (Ca^{II})* known as H and K, and the lines of hydrogen, constituting one of the most important characteristics of these spectra. The Ca^{II} lines reach maximum intensity in class G, where the surface temperatures are 5000 to 6000 degrees, and the hydrogen lines are weaker, with an increase in the concentration of lines due to neutral atoms. Among F-type stars may be mentioned Canopus and Procyon. Class G contains our own Sun, Capella and α Centauri; because of the great apparent brilliancy of the Sun compared with the other stars, it is obviously a relatively easy matter to study its spectrum in detail.

In type K, the cooler arc lines are more numerous and the hotter spark lines less common; the spectrum is less bright

* Calcium atom ionized by the loss of an electron.

in the violet region, but more so in the red. The lines due to ionized calcium are very noticeable, and metallic lines are numerous and intense; bands due to molecules such as titanium oxide are also evident. Stars of type M have surface temperatures below 3400 degrees, and the cool flame lines, which are metallic, have become intense. Bands due to various metallic compounds are also prominent.

From what has been said, it can therefore be seen that there are many stars much larger and more luminous than the Sun. In order to allow us to make a comparison of the properties of the stars by using their 'apparent magnitude',* which is the brightness as seen in our sky and is thus a function of distance, we need to deduce the 'absolute magnitudes' of the stars. This absolute magnitude is the apparent brightness which a star would appear if moved to a unit distance in space. Since the 'astronomical unit', or distance between the Earth and the Sun, is patently too small for this purpose, the unit adopted by the International Astronomical Union is 10 parsecs,† a value equivalent to 32·6 light-years.

From this definition of absolute magnitude, we find that the Sun has a value of +4·8. A star of this magnitude is easily visible to the naked eye, but since the Sun is so close

* The apparent magnitude is conventionally given by Pogson's formula:

$$\log \frac{l_m}{l_0} = -0{\cdot}4m$$

where l_m and l_0 are the apparent brightness of a star of magnitude m and magnitude 0 respectively. A star of magnitude 0 is bright to the naked eye, such as the star Vega (α Lyrae) which has an apparent magnitude of zero.

† The parsec is the distance a star would have if its parallax Π were equal to one second of arc. The absolute magnitude is given by:

$$M - m = 5 - 5 \log d$$

where M is the absolute magnitude and d is the distance expressed in parsecs.

B

on the astronomical scale its apparent magnitude is much greater, and amounts to −26·7.

The apparent magnitude of Sirius is −1·6; it lies at a distance of 8·6 light-years, and has an absolute magnitude of +1·3, with an intrinsic brightness 27 times greater than that of the Sun. Antares (α Scorpii), at about 360 light-years, has an apparent magnitude of +1·2, and so an absolute magnitude of −4·0; it is therefore more than 3500 times as luminous

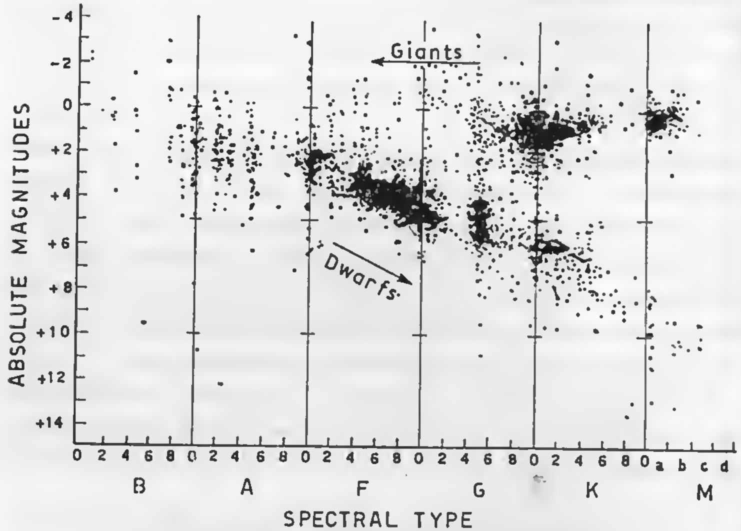


FIG. 1. The Hertzsprung-Russell (H-R) Diagram.

as the Sun. One of the most luminous stars in the Milky Way system, Rigel (β Orionis), with an apparent magnitude of +0·3 and at a distance of 470 light-years, has an absolute magnitude of −5·5, and is thus 14,000 times more luminous than the Sun. When it became possible, about fifty years ago, to measure the distances of the stars by means of the annual parallax method, evidence was obtained that stars in the same spectral group were of widely different dimensions, and the well-known Hertzsprung-Russell Diagram (fig. 1) was drawn

up by the two astronomers of that name. With the abscissae denoting the spectral type according to the Draper classification from B to M, and the ordinates showing the absolute magnitude from −4 to +15, it is clear that there is a principal series which begins with stars of negative absolute magnitude and continues downward to stars in group M, which have positive absolute magnitudes. The place of the Sun in this series may be determined without difficulty, since it belongs to type G0 and has an absolute magnitude of +4·8. The principal series shown in the Hertzsprung-Russell Diagram is generally called the 'main sequence'.

Main sequence stars of positive absolute magnitude are known as 'dwarfs'. There exists another group of stars from type G to M which is around zero absolute magnitude; these stars are therefore highly luminous, and are known as 'giants'. Between the two main areas on the diagram, and also under the main sequence, two large empty spaces will be noticed. Stars with other characteristics are found in these regions, but are relatively scarce.

In the region of the giant stars, there are stars with luminosity 100 to 10 thousand times greater than those of the same spectral type which belong to the main sequence, and which, moreover, have radii from ten to a hundred times larger. Some stars of the same spectral type as the Sun are more luminous and much larger than the giants, and are known, appropriately enough, as 'supergiants'. Their absolute magnitudes range between −4 and −7.

It must be understood that the difference between stars of the same spectral type – dwarfs, giants or supergiants – is one of size of radiating surface. Because they have similar spectra, their surface temperatures will be much the same. In general, it may be said that the surface temperature of a G0-type giant is approximately 5600°, while that of a G0-type dwarf, such as the Sun, is some 6000°.

The Size and Radiation of the Sun

The mean apparent diameter of the Sun is about $32' = 1920''$ $= 0{\cdot}0093$ radian. Therefore at the principal focus of an objective or a parabolic mirror of 1 m focal length, an image of roughly 1 cm is produced; at 2 m, an image of 2 cm and so on. The Sun's parallax, which is the equatorial radius of the Earth as it would appear if viewed from the mean Sun-to-Earth distance, is $8''{\cdot}80$, so that the 'astronomical unit', or mean distance, is

$$1{\cdot}4945 \times 10^8 \text{ km} = 1{\cdot}4945 \times 10^{13} \text{ cm}$$

The diameter D of the Sun is about 109 times that of the Earth; therefore

$$D = 1{,}390{,}600 \text{ km}$$

and radius $R = 695{,}300$ km

On the Sun's disk, $1''$ is equivalent to 725 km, so for an object on the Sun to be visible at all as seen from the Earth it cannot have a diameter less than several hundreds of kilometres.

From the law which governs the movement of the Earth around the Sun, the solar mass ($M_\odot$) is found to be 331,950 times that of the Earth; hence $M_\odot = 1{\cdot}983 \times 10^{33}$ g.

The gravitational acceleration at the Sun's surface is 28 times greater than at that of the Earth, and the Sun's average density is 1·4 times that of water. It is therefore obvious that the Sun cannot be a solid body like the Earth; the materials of which it is composed have a much lower mean density.

One of the most important problems yet to be solved in solar physics is the determination of the total amount, and type, of radiation emitted by the Sun. Of course, only a minute part of the total radiation so emitted falls on to the Earth, after having first passed through our atmosphere. As a first approximation one may consider the Sun as a 'perfect radiator', or black body, and by applying the Stefan-Boltzmann law of radiation for black bodies, the total intensity of radiation may be calculated; moreover, from Planck's formula, which is concerned with the temperature of a black body and that part of the spectrum where the greatest amount of energy will lie, the energy distribution can be found. From these calculations the mean temperature of the Sun's atmosphere may be deduced.

In practice, measures are made of the amount of solar radiation falling each minute on a surface of 1 cm^2 (square centimetre) exposed perpendicularly to the Sun's rays, and reducing the observations to the appropriate value as if they had been made with the Sun lying at its true mean distance. The result is expressed in gram calories. Measures of this type were carried out in 1887 by Pouillet, using his pyrheliometer; a flat-bottomed, blackened copper vessel oriented toward the Sun. The vessel is filled with water, in which a thermometer is placed. Taking the thermal capacity of the apparatus into account, the rise in temperature indicates the intensity of the solar radiation at the known zenith distance of the Sun. Extrapolating these measurements to the estimated limits of the Earth's atmosphere – that is to say, the point at which the effect of atmospheric absorption may be disregarded – Pouillet obtained a first approximation for the solar radiation received outside the atmosphere – the 'solar constant'.

Later experiments led on to the development of various types of pyrheliometers, in particular those due to Angström and Abbot, with which many measures have been taken at different localities and at different heights above sea-level. Measurements have also been recorded up to altitudes of around 100 km. The figures so obtained for the solar constant are not in full agreement, but the generally accepted value is:

$$2{\cdot}00 \text{ cal cm}^{-2}\text{min}^{-1} = 8{\cdot}36 \times 10^7 \text{ erg cm}^{-2}\text{min}^{-1}$$
$$= 0{\cdot}140 \text{ watt cm}^{-2}$$

The Earth receives only a small part of the radiation emitted by the Sun. Since the radiation falls on a sphere of surface area $4\pi R^2$, where R is the distance between the Sun and the Earth, and since, moreover, that this distance is 200 times greater than the solar radius – the derived value of the solar constant should be multiplied by about 40,000 in order to obtain the Sun's total radiation, E, which is therefore given by

$$E = 6{\cdot}5 \times 10^{10} \text{ erg cm}^{-2}\text{sec}^{-1}$$

Assuming that the Sun acts as a black body, the application of the Stefan-Boltzmann law yields what may be termed the effective temperature (T_e) of the Sun, and this is related to the energy E by the relationship

$$E = \sigma T_e^4$$

where σ is a constant denoting the rate of radiation.

Using as the radiation constant the value

$$\sigma = 5{\cdot}67.10^{-5} \text{ erg cm}^{-2}\text{sec}^{-1}\text{deg}^{-4}$$

we obtain

$$T_e = 5780 \text{ degrees K}$$

For the study of the photosphere – that is to say the surface of the Sun which is seen with the naked eye or with an optical telescope – it is necessary to consider the absorption lines in the spectrum, known as Fraunhofer lines, after their discoverer. From this, it is possible to derive the distribution of energy in the continuous spectrum which makes up the background. With small-dispersion spectroscopes, the greater part of the Fraunhofer lines cannot be resolved but there is a drop in the brightness curve in the region below 5000 A, where the lines are very dense.

Direct observation of the Sun's disk shows at once that it is not uniform in brightness; the centre is the most brilliant, and the intensity falls off toward the limb, while the colour

changes from yellow to orange-red. From this it is evident that the transparent outer layers of the Sun absorb the shorter wavelengths, and that the temperature is highest near the centre of the disk. In point of fact, at the centre of the disk the observed radiations come from the deeper layers, whilst near the limb the radiation comes from layers nearer the Sun's surface. A series of observations of the so-called *darkening* of the limb areas has made it possible to deduce the vertical temperature gradient in the photosphere; from this, it is possible to derive a relationship between the intensity of radiation from the photosphere (as measured at a distance r from the centre of the solar disk) and the intensity of radiation actually measured at the centre for different wavelengths.* The following table of λ and ϱ illustrates the point.

λ (in *A*)	$\varrho=0{\cdot}00$	$\varrho=0{\cdot}30$	$\varrho=0{\cdot}60$	$\varrho=0{\cdot}82$	$\varrho=0{\cdot}92$	$\varrho=0{\cdot}95$
3,220	1	0·93	0·80	0·60	0·45	0·38
4,000	1	0·95	0·83	0·64	0·50	0·43
5,000	1	0·97	0·87	0·71	0·58	0·52
6,000	1	0·97	0·89	0·76	0·65	0·59
8,000	1	0·98	0·92	0·82	0·73	0·69
10,000	1	0·99	0·93	0·86	0·77	0·74
20,000	1	—	0·96	0·92	0·88	0·85
60,000	1	—	0·98	0·96	0·94	0·92

* If R is the sun's radius, r the distance from the centre of the solar disk where the intensity of the photospheric radiation has been measured, then:

$$\rho = \frac{r}{R} = \sin\theta$$

At the centre of the disk $\theta = 0$.

Chapter II

THE PHOTOSPHERE OF THE SUN AND SUNSPOTS

When the photosphere is observed with an adequate telescope under good conditions, it presents a 'granulated' appearance.* The French astrophysicist Janssen was among the first to photograph this granulation, which he termed the 'réseau photosphérique'. The general appearance is that of many brilliant granules orientated at random, but almost equally spaced-out in a roughly regular pattern crossed by dark zones. Near the centre of the disk, the pattern is quite regular, but perspective effects result in its being deformed near the solar limb. To account for this pattern, the sizes, movements and brilliancies of the granules have been measured, and photographs of them have been taken from high altitudes, using balloons and rockets, so as to minimize the disturbances due to currents in the Earth's lower atmosphere.

It has been suggested that the granulation may be explained by irregular convection currents, with columns of from 1000 to 4000 km in height rising from the Sun's interior, and Richardson and Schwarzschild obtained Doppler measurements of the spectra of the granules, obtaining an average velocity of 0·4 km/sec. The darker zones may possibly be due to a descending flow of gases – that is to say,

* In order to study the Sun safely and easily, the image is projected on to a white screen at the focus of the eyepiece, and direct observation even with a colour filter is not recommended.

to columns moving in the opposite direction to those which cause the granulation. The brightness difference between the clear granules and the darker regions may be accounted for by a temperature difference of about 100°; it is possible that greater differences of temperature do exist, but difficulties of observation make this point hard to establish.

The difficulty of investigating these important characteristics of the solar granulation is due largely to the effects of the Earth's atmosphere, which, even at its best, is always unsteady. Useful photographs (such as Janssen's) have been obtainable only at high-altitude observatories under exceptionally good meteorological conditions. In recent years it has however become possible to make use of space research methods, in which the necessary instruments are taken beyond the Earth's atmosphere. These new methods will increase our knowledge of the structure of the photosphere, as well as shedding new light on many other problems. At the Princeton University Observatory, under the leadership of M. Schwarzschild, experiments have been recently carried out in which the Sun's surface has been photographed from the upper part of the troposphere, which extends from 8 to 16 km above the surface of the Earth. The telescope used in this work is a Newtonian reflector with a 12-in. quartz mirror. Using a ciné-camera and 35-mm film, the system enables a section of the Sun's surface equivalent to an area of 55,000 × 80,000 km to be covered at exposures of a millionth of a second. The instrument and its mounting are attached to a large balloon filled with helium, ascending to an altitude of 25,000 m, at which height the camera is automatically brought into action. The equipment is subsequently returned to the ground by parachute. From the many photographs so obtained, three principal features emerge. The brightest granules are well-defined, and vary considerably in size. Many of them measure only 300 km or so in diameter – too small

to be recorded individually on photographs taken from ground level – but others have diameters up to approximately 1600 km. Secondly, most of the granules are seen as irregular polygons. Thirdly, the dark areas are more clearly shown than had previously been possible, and appear as networks of lanes or 'canals' running between the bright granules.

We know that vast amounts of heat flow from the deep layers of the photosphere, and that these must result in the formation of tremendous convection currents. From laboratory experiments it has been found that when a layer of paraffin wax 3 to 4 mm in thickness is heated in a flat dish, the surface of the liquid breaks up into the form of clearly-defined polygons; this phenomenon has been termed 'stationary convection'. If the layer of wax is around 13 mm in depth, the polygons become irregular in shape and size, and are separated by dark lines, so presenting an appearance similar to that of the Sun's surface; this is referred to as 'non-stationary convection'. An interesting fact has thus been established from the photographs: the appearance of the solar surface is due to effects of 'non-stationary' convection. There are, then, new factors to be investigated in the flow of the Sun's heat outward from the centre of the disk, and these will yield greater knowledge of the solar interior. This, in turn, will be of the utmost value in investigations of the mechanism of other stars. The regular pattern of the solar granulation is an indication of the relatively calm state of the Sun's surface, undisturbed by the periodical upheavals. By direct visual or photographic observation, the disturbances first appear as isolated darkish points against the luminous background of the photosphere. They have been called 'pores', and may quickly increase in number and size, giving place to the formation of spots or groups of spots (plates I and II).

Sunspots, as their name indicates, are relatively small areas

of the solar surface, and are darker than the adjacent regions. The more regular spots generally consist of a uniformly dark, circular central nucleus, termed the *umbra*, surrounded by a lighter *penumbra*, a larger zone apparently formed by rays emanating from the centre of the umbra. Spots may vary greatly in size. Some are isolated, but most appear as members of complex groups, covering several thousandths of the area of the Sun's visible disk. An umbra of about 2′ diameter (90,000 km) is regarded as decidedly large. In comparison with the brilliance of the photosphere, the average spot-brightness is about 0·4, though the spots differ appreciably between themselves.

As well as considering the structure of individual spots, we must pay attention to the way in which the spots appear and disappear, their frequency, their distribution on the Sun's surface, and their relationships to the phenomena invisible to normal observation in white light. Among the visible effects are those associated with regions in which spots are found, the so-called *faculae*, which are more or less irregular in shape, and may be very extensive. They appear brightest, as their name implies, near the Sun's limb, but fade as they move toward the centre of the disk, and eventually disappear. This fact establishes the existence of an absorbent atmosphere over the Sun's surface, which extends beyond the photosphere itself. Spectroscopic investigations have yielded a great deal of information as to the nature and composition of both spots and faculae.

The frequency of sunspots is very variable, and this also applies to various phenomena associated with the spots themselves – all of which demonstrate remarkable disturbances in the photosphere and in the higher layers of the Sun's atmosphere. At times the photosphere is completely free of spots; at other times there may be many groups scattered about the disk.

Statistical investigations into spot-frequencies have been made, the basic method being to count the numbers of groups and single spots visible on each day. In 1849 Wolf* of Zürich put forward the formula for the relative number of spots, R. His calculation of how many groups of spots are present and how many are single spots is somewhat arbitrary, and does not give precise results with regard to solar activity; nevertheless, sufficiently acceptable results have been obtained back to the year 1749, and work is still going on today, in observatories throughout the world, to arrive at accurate daily values of R, sometimes called the 'Wolf number'.

A more exact study of solar activity in relation to spot-phenomena is being made by using telescopes, horizontal or vertical, of extremely long focal length. Photographs are taken, and the areas covered by umbra and penumbra are measured, so that for each day it is possible to work out just how much of the disk was affected. This method was begun at Greenwich in 1874, by Carrington, who published 'Greenwich Photoheliographic Results' based on data obtained at different observatories. The area covered by the disk-photograph was measured by a grid divided into small squares; all the measurements were then adjusted to represent areas equivalent to the relevant area at the centre of the Sun's disk. At times of low activity the total area covered was found to be from 10 to 100 millionths of the full disk, while at maximum activity the average might amount to as much as 1400 millionths of the full disk. (One-millionth of this is equivalent to $3{\cdot}02 \times 10^{16}$ cm^2.) When the disk is at

* Wolf's formula is $R = k(10g + f)$, where R is the relative number of spots, k a constant dependent on the instrument and the method used for observation (direct visual or photographic, according to the state of the atmosphere), g the number of groups, and f the number of single spots.

its most disturbed, the area covered may be as much as 2000 millionths. It may therefore be said that the relative or Wolf numbers give good approximate values for solar activity. If F denotes the area according to the Greenwich method, and R the relative number, then $F = 16{\cdot}7R$.

As early as 1612, Galileo had discovered that the spots and faculae move regularly from east to west in curves parallel to the Sun's equator, and that when formed on the far side of the solar globe they make their first appearance at the eastern limb. Very large spots have been observed over several complete rotations of the Sun, and by timing the successive passages across the central meridian it has been concluded that the rotation period is about 27 days. However, this is the synodic period, not the true one, because we have to allow for the motion of the Earth round the Sun.*

In order to obtain precise estimates of features on the disk, and to determine the rotation period, a system of co-ordinates referred to the equator and to the Sun's axis has been adopted. The central meridian of the disk is used as the meridian of reference for east–west longitude. The solar equator is inclined to the ecliptic by an angle of approximately 7°, i.e. an angle of 26°·4 with the Earth's equator. The Sun's rotation period as deduced from observations of the spots is of course approximate only, because the spots have individual motions as well as their apparent drifts across the disk caused by the solar rotation. Because the Sun's equator is inclined to the ecliptic, the apparent paths of the spots are not straight lines, but may be likened to ellipses which are orthographic projections of the solar parallels of latitude as seen from the Earth; the apparent

* The true period is expressed by $1/T - 1/E = 1/S$, where T is the true period, E the length of the year, and S the observed synodic period. Given that $E = 365{\cdot}25$ days and that $S = 27{\cdot}25$ days, then $T = 25{\cdot}35$ days.

paths are straight lines only when the Earth is at one of the two points in its orbit where the ecliptic cuts the equator. At all other times the Sun's axis is inclined to the ecliptic; the angle varies between zero and 7°. Moreover, the inclination means that relative to the north–south line across the disk, the Sun's axis lies at an angle with a maximum value of

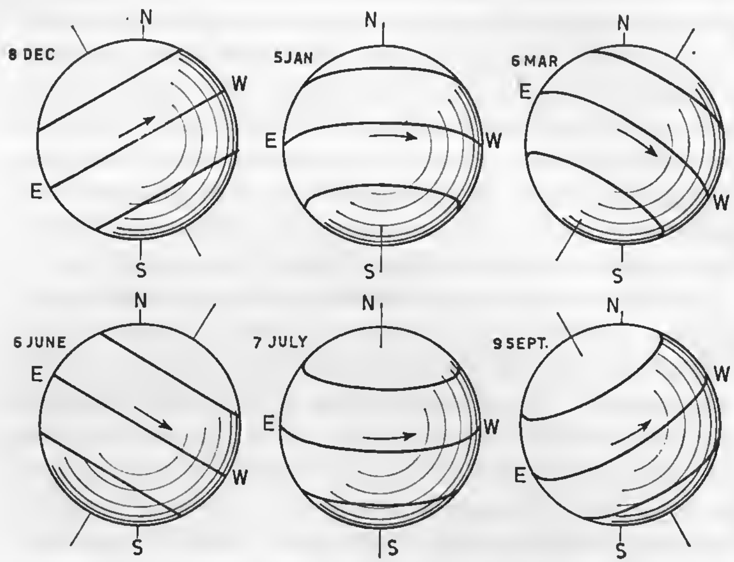


FIG. 2. Inclination of the Sun's axis, with respect to the Earth, for different seasons.

26°·25 east or west. Various annual publications publish physical tables for the Sun which give the positional angle of the solar axis, the inclination (identical with the heliographic latitude of the Earth), and the heliographic longitude of the centre of the disk, for 5-day intervals (fig. 2).

The length of the Sun's rotation period, or – more accurately – for the various surface layers, may be determined by several methods.

The first and simplest of these, used by the early observers, was based on the reappearance of the same spot at the same position – that is to say, when it passed the central meridian. Faculae could also be used for these measurements, though less easily. With the discovery of other phenomena such as bright flocculi and dark filaments, the method could be extended. Later, with the development of spectral analysis, it became possible to measure the velocity of approach or recession of the Sun's limb respectively east and west relative to the Earth, first visually and subsequently by means of photographic techniques. Important results were obtained with regard to the depth of the layer in which the various phenomena were seen. In 1863 Carrington discovered a systematic change in the angular velocity of rotation as a function of latitude, and he obtained a figure of 25 days for the sidereal period at the equator; this corresponded to a diurnal angular velocity of 14°·42, which at a latitude of 35° was reduced to about 1° per day. Since spots (as we shall see) appear mainly in the equatorial regions, and are seldom seen beyond ±40° latitude, the method cannot be extended to the poles, but at least it is obvious that the Sun does not rotate as a solid body. Carrington's first measurements yielded the following results:

Latitude (degrees)	*Rotation Period (days)*
0	25·0
±10	25·2
±20	25·7
±30	26·5
±40	27·4

The last value in this table is very uncertain, because of the rarity of spots in these latitudes. It is possible to represent, approximately, the mean rotational velocity ω_m as a function of heliographic latitude by using an empirical formula.* Such

* $\omega_{\mathrm{m}} = 14°{\cdot}38 - 2{\cdot}77 \sin^2 \phi$, where ϕ = latitude.

calculations were made by Carrington in 1863, and later by Newton and Nunn on the basis of observations at Greenwich of recurrent groups of spots in the course of six 11-year cycles between 1878 and 1944. From this, an expression for the velocity of rotation of the Sun at various latitudes is derived, and although the spots themselves have individual movements, average values for ω can be obtained for different latitudes:

ϕ (*degrees*)	ω_m (*degrees*)
0	14·40
±10	14·31
±20	14·06
±30	13·69

Determination of a value for the rotation period from observations of the motions of faculae is much less exact, due to the absence of stable, clearly-defined features, together with the difficulty of carrying out the observations in limb areas. However, an average from the many observations made gives an empirical formula similar to that obtained from the spots.*

The displacements noticed when the Fraunhofer lines obtained from the centre of the disk are compared with those obtained at the solar limb, at once suggests the possibility of using the spectroscope to measure the Sun's rotation. The Sun rotates in the same sense as the Earth, so that the eastern edge of the disk is moving toward us, while the western edge recedes. This produces a Doppler effect†; the shift amounts to double the velocity of rotation of the solar disk, either at the equator or at any other parallel. It is easy to appreciate the advantages of the spectroscopic method as

* $\omega_f = 14°{\cdot}54 - 2°{\cdot}81 \sin^2 \phi$.

† The Doppler effect is based on the fact that if a source of radiation of a particular wavelength λ_0 is seen by an observer travelling at a velocity v, then the wavelength appears to take on a new value λ, given by $\lambda = \lambda_0(1 + v/c)$, where c is the velocity of light.

compared with the older studies of spots and faculae. For one thing, it may be extended to the highest latitudes, beyond the region where the spot-movements cease to give tolerable results; for another, it eliminates the errors due to individual spot-movements. The method was first used by Vogel in 1871. Since then many determinations have been made, first visually and later – more precisely – by photographic techniques.

Detailed studies were carried out by Adams, at Mount Wilson, between 1906 and 1908; the work has since been continued by other astrophysicists at the same observatory, using solar tower-telescopes (which will be described in the next chapter). The mean value for the linear equatorial velocity,* obtained from the Fraunhofer absorption lines at the extreme limbs, is approximately 2·00 km/sec, or 14°·23 per day, a smaller value than that obtained from spot-studies. Similar observations made elsewhere give results which differ appreciably. These discrepancies may be due to various causes; different instrumentation, diffused light, or even actual variation of the period itself. It seems that diffused light in the Earth's atmosphere and its effects on instruments can reduce the values by about 4 per cent. Results obtained at the Ottawa Observatory give a different formula for the rotation period.† Moreover, Adams' work shows that the angular velocity of rotation increases with increase of the altitude over the Sun's surface; similarly the

* The velocity of rotation, latitude and Doppler effect may be expressed as follows:

$$V_\phi = \frac{\Delta\lambda . c}{\lambda \sin \theta \cos \phi_0}$$

where λ = wavelength, c = velocity of light, ϕ_0 = latitude of the centre of the Sun, and θ = the distance from the central meridian of the point of observation to the edge at latitude ϕ.

† $\omega = \omega_0 \cos^n \phi$, where n = 0·315 and $\omega_0 = 14°{\cdot}37$.

slowing-down of the period toward the poles decreases with altitude.

It will now be shown how it is possible to distinguish the various levels of the solar atmosphere by considering the Fraunhofer lines formed by different elements such as iron, calcium and hydrogen. It may be said that the photosphere, i.e. the layer including the spots, has a velocity about 1 per cent lower than that of the faculae and flocculi. Measuring the period of rotation by the strong hydrogen line Hα, it is found that the relevant layer has a velocity of some 3 per cent greater than that of the photosphere. Measurements of filaments or prominences made by L. and M. D'Azambuja at Meudon give another different value for angular rotation of the layer containing these features.* The slowing down of the filaments towards the poles is therefore less marked than in the case of the spots.

With regard to any possible periodical or secular variation, it must be said at once that results so far are negative. The spots inevitably give values which are by no means exact, but over five solar cycles, from 1878 to 1933, no significant variations in the period of rotation were detected. On the other hand, observations at Mount Wilson between 1923 and 1933, using the 150-ft solar tower and a 75-ft spectrograph, showed a difference of $0{\cdot}10 \pm 0{\cdot}01$ km/sec, which appeared to be a true value, and which could be related to the 11-year cycle or to the magnetic 22-year cycle.

Level and Life of the Spots

By studying the spots and their east–west drift across the Sun's disk, Wilson at Glasgow, in 1774, noticed a phenomenon which gave a simple explanation of the problem of the level of spots in the photosphere. Wilson noted that a spot always appeared oval in shape when near the Sun's limb.

* $\omega = 14^\circ{\cdot}42 - 1^\circ{\cdot}40 \sin^2 \phi - 1{\cdot}33 \sin^4 \phi$.

Now if the umbra is roughly circular, and is surrounded by a regular concentric penumbra, then when such a spot is near, say, the eastern limb, the western part of the penumbra will be apparently compressed in comparison with the eastern part. The reverse will be true for the spot when near the western limb, and this can only be caused by perspective effects. If the nucleus is at a lower level than that of the photosphere, the spot will assume the shape of a funnel and these perspective effects will occur. The depth of this funnel may be established by measuring the size of the penumbra when the spot passes the central meridian, and the angle between the disk-centre and the umbra when, due to perspective, the penumbra either east or west of the nucleus disappears. (It is, of course, essential that the spot should not genuinely change in form during the period of observation.) Not all spots show this 'Wilson Effect', but further investigations have confirmed that in general the umbra of a spot is at a lower level than the penumbra and the photosphere, with a depth-difference of not more than 1″, equal at the distance of the Sun to 750 km.

Observations have been made with regard to the birth and development of a spot or spot-group. First, several small pores appear on the surface and join together into two spots; the 'leader', P (preceding), is usually the more compact, and has a longitudinal motion. A bridge is gradually formed by smaller spots, and thus becomes the 'trailer' or following spot, F. The spot P then becomes circular, diminishes in size, and finally breaks up into a number of pores, which in turn give rise to new spots.

This sequence of spot-development may be fitted into a classification introduced by Waldmeier and now generally adopted. It includes nine separate classes. A typical example of this is shown in fig. 3. A small group will reach stage A or B, and, subsequently, A-B-A. A medium-sized group will

develop, in about five days, along A-B-C-B-A; a large one may reach stage F in 10 days or so, and the cycle will be completed in about 60 days (roughly two rotations of the Sun).

As will be shown below, the development and appearance of the spots is intimately associated with their magnetic

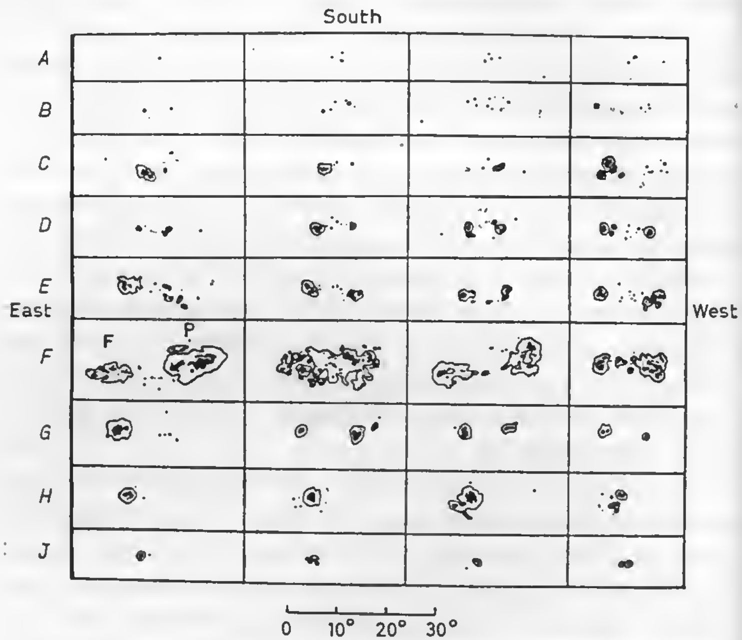


FIG. 3. Sunspot group classification, according to Waldmeier.

properties. In class E the length of the group attains 10°; in class F, 15°. Spots in class H have diameter about 2°·5. In fig. 4, the daily number of outbursts in the chromosphere (flares) is plotted against the various spot-classes and relative numbers, while the total area covered by the groups is expressed in millionths of the visible disk.

The latitudinal or longitudinal motions of the spots across

the photosphere may be either uniform or irregular. The individual movements of long-lived spots have been studied at Greenwich. Latitudinal motion is usually slight; of the order of 0°·1 per revolution. It is of interest to note that the

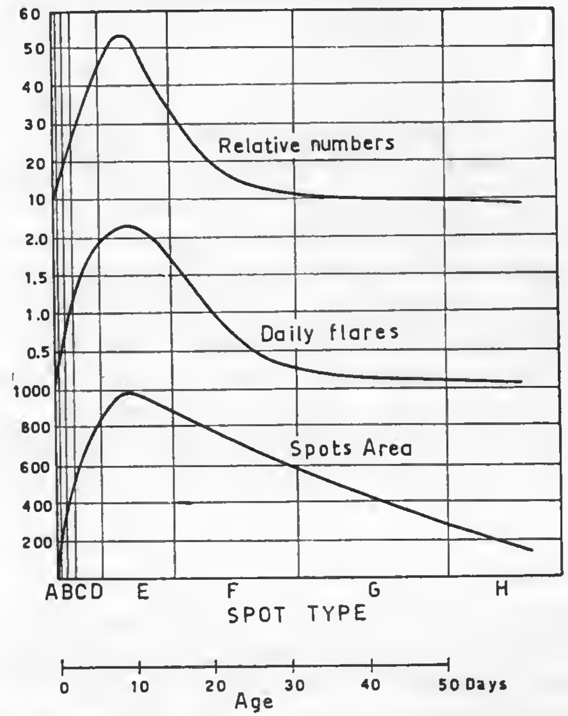


FIG. 4. Relative sunspot number, number of flares, and sunspot area as a function of their development.

general trend of the spots is toward the equator throughout the 11-year solar cycle, and amounts to roughly 0°·14 per sidereal revolution, though of course the movements of individual spots are not easy to determine. The longitudinal systematic motion is more obvious, and Maunder suggested that it must be related to the age of the spots. During the

first two days, the spot P in a group moves rapidly towards the west at a velocity of about 1°·0 per day; this then decreases until the fifteenth day, when the average velocity appropriate to the latitude is reached. By the twentieth day the motion is retrograde to a rate of approximately 0°·06 per day. At the same time, the size of the spot alters, increasing quickly until about the tenth day. The movement of the following spot, F, is much slower than the average for the latitude, particularly at the time of its formation, when its mean velocity is 0°·3 toward the east. An increase in size takes place, reaching a maximum about the third or fourth day, and is followed by a slow decline. At Greenwich, investigations have also been made of the proper motions of the faculae, comparing the mean latitude during one rotation with the average of several. In the zone between 0° and ±40° latitude, these investigations show a movement of the faculae, away from the equator and toward the poles, of 0°·8 during each rotation of the Sun. This trend is more marked in higher latitudes, and may reach as much as 1°·6 in the zone ±30° to ±40°.

The Eleven-year Cycle

In 1843, after observations extending over twenty years, Schwabe decided that the frequency of sunspots was regulated according to a definite cycle of about 10 years. Wolf then examined all the available records back to the time of Galileo (1610) and concluded that the period was 11·1 years. This was, however, an averaged value, since the individual cycles seemed to have a wide range of from 7·3 to 17·1 years. Moreover, the intensity of maximum activity was not always the same; for example, the maximum of 1957–8 was some four times as active as that of 1816, the feeblest maximum observed since Galileo's time. These considerable variations may possibly have their origin in the overlapping of other

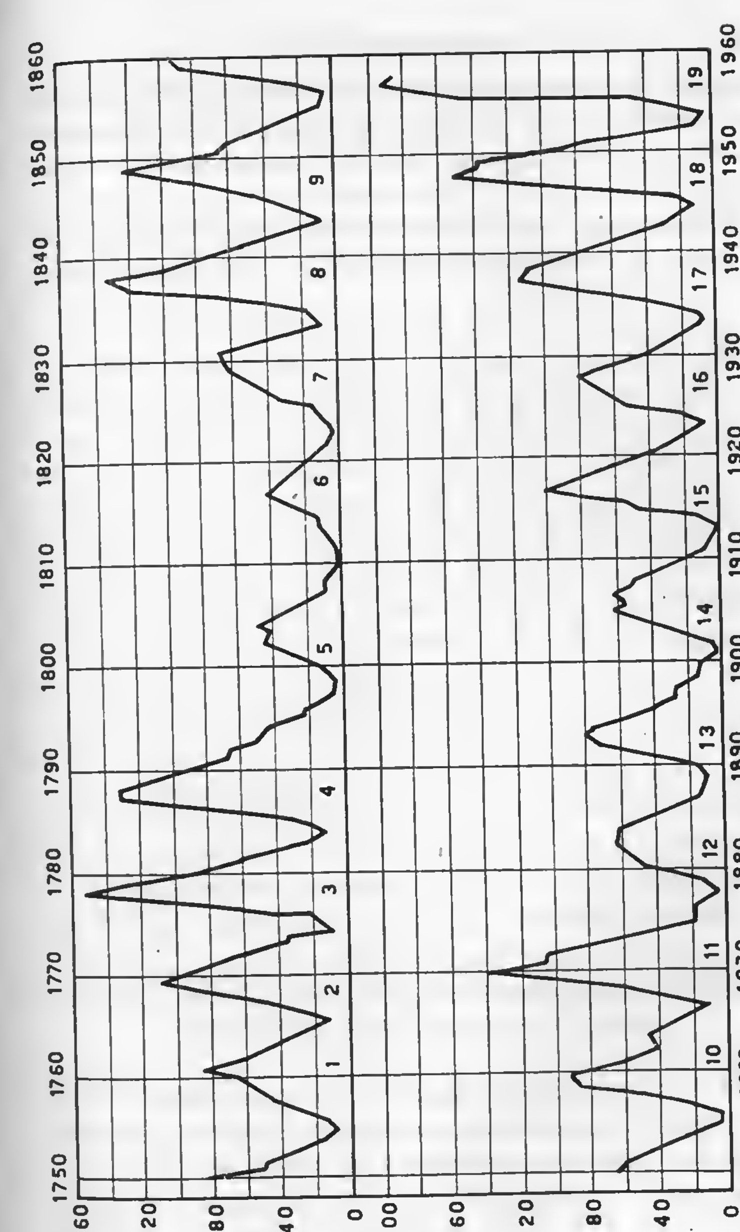


FIG. 5. Annual average of relative sunspot numbers, 1750-1958.

periods. By mathematical analysis, attempts have been made to investigate this problem. Correlation has also been attempted with tree-rings, which clearly show an 11-year cycle.

From graphs of the relative numbers and sizes of spots, it is found that the time taken to rise from minimum to maxi-

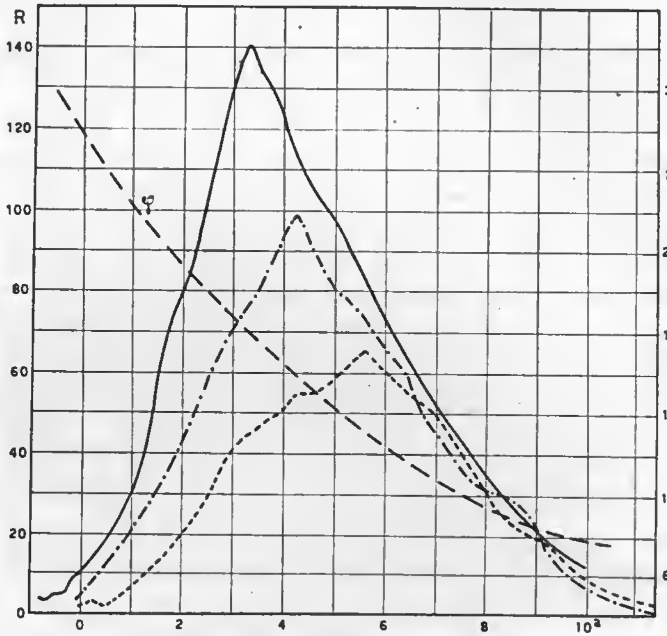


FIG. 6. Relative sunspot numbers for cycles of weak, medium and strong intensity, and the migration in latitudes, ϕ, during the 11-year cycle; the abscissa shows the time-lapse since minimum.

mum is greater than the period of the subsequent fall. The mean period from minimum to maximum is about 6·6 years; from maximum to minimum, only about 4·5 years. The graph of the solar cycles from 1749 to the present day is shown in fig. 5; it will be immediately evident that there are

marked differences, both in duration and in intensity, between the separate cycles. If the maxima of the cycles are made to coincide, it is seen that the trend of the curves of frequency may be ruled by a parameter R_M, which represents the greatest relative monthly number for a given cycle.* Fig. 6 shows typical frequency curves plotted against the mean of high, medium and low values of R_M. High values are 3-4-8-9-11-17-18 and 19; medium values, 1-2-10-13-15; and low values, 5-6-7-12-14 and 16. From this result one can see that it is possible to predict the behaviour of a cycle with reasonable accuracy – once the cycle has started; we cannot yet make long-term predictions concerning the sequence of high and low cycles. There is certainly a lengthy period of oscillation of the intensity of the maximum; it seems that R_M increases and decreases over an interval of around 7 cycles. A maximum for R_M was observed in 1778; another in 1860, and again in 1937, followed by two really remarkable maxima – those of 1947 and 1957.

The general trend of solar activity is most irregular and cannot be expressed even by a monthly or annual average. The changes may be very striking; there may be a very high relative number, perhaps greater than 200, occurring near a low one of about 20. These fluctuations may extend over a few days, or perhaps several months, with no detectable periodicity. However, periodicity is noticed as the Sun rotates, and may be followed over several months. Due to the limited lifetimes of the spots, periodicity measurements are

* Waldmeier has found that the duration of the rise from minimum to maximum could be represented for even cycles by the expression

$$\log R_M = 2{\cdot}69 - 0{\cdot}17T$$

and for odd cycles by

$$\log R_M = 2{\cdot}48 - 0{\cdot}10T$$

which is to say that T decreases with the increasing intensity of the maximum.

possible only because spots often return to the same regions of longitude.

The numbers and sizes of spots vary according to the 11-year cycle, and this is also true of their positions and distribution on the Sun's surface. This fact is of the greatest theoretical importance in solar physics, and is related to the magnetic cycle. Even the earliest solar observers had noticed that spots usually appear in two zones parallel to the equator, being limited to the northern and southern zones from 0° to 40°. After a minimum, the first spots of a new cycle appear at latitude $\phi = 30°$ approximately. As the cycle proceeds, the spot-groups move toward the equator, reaching a maximum when $\phi = 15°$ approximately; the last spots of the cycle appear at a mean latitude $\phi = 8°$. The first spots of a new cycle appear before the disappearance of the last groups of the previous cycle. For example: the last five cycles have varied from 11·8 to 14·4 years, with an overlap of from 1·6 to 3·3 years.

Waldmeier also investigated the relationship between the movements of the spots and their frequency of appearance. If we take R_M as being the largest monthly value during a particular cycle, ϕ_{-50} the mean heliographic latitude of the spot-zone, there will be 50 rotations before maximum is reached; ϕ_m relates to the maximum and ϕ_{+50} that after maximum, so that Waldmeier's formulae become:

$$\phi_{-50} = 17°{\cdot}6 + 0{\cdot}084R_M$$
$$\phi_m = 8°{\cdot}2 + 0{\cdot}070R_M$$
$$\phi_{+50} = 5°{\cdot}4 + 0{\cdot}043R_M$$

This is illustrated in fig. 7; the abscissa represents the distance from maximum in period of rotations, and the ordinate refers to mean heliographic latitude. From this diagram, where zero on the time-scale represents a maximum, the following laws are derived: the zone of the latitude is at

its highest when R_M is greatest; the zone extends from 15° to 30° heliographic latitude; spots where $\phi > 40°$ are rare, always small and have short lifetimes. In 1846 one spot was discovered at 50°, and in 1915 another appeared at 60°, while

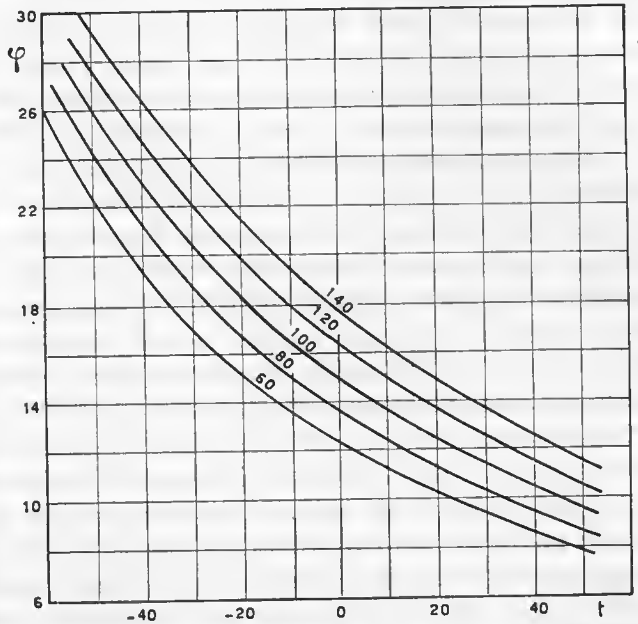


FIG. 7. Migration of sunspots as a function of R_M, t on the abscissa showing the time-lapse since maximum in periods of rotation (Waldmeier).

small pores have been observed briefly at latitudes up to 75°.

No laws governing the distribution of spots in heliographic longitude have yet been found. In general, the spot-activity is not of uniform intensity, but is concentrated in definite regions, and varies in duration. The appearance of spots in such regions may go on for several years; at times the chains of spots extend over as much as a quarter of the

Sun's circumference. Moreover, the appearances of spots in one hemisphere is not independent of activity in the other hemisphere. It is common for a group in one hemisphere to be linked with a corresponding group at the same longitude in the other hemisphere.

The frequency of spots decreases rapidly in relation to their lifetimes. More than half of all groups have a life of less than two days, and more than 90 per cent last for less than 11 days. The mean lifetime is a function of latitude; at 40° it is 2 or 3 days, reaching a maximum of 5 days at 7°. A spot with a lifetime of 10 days may extend over an area of 100 millionths of the visible surface of the Sun. A spot with a life of 40 days may be four times larger than this. The most extensive groups may last over a period of four rotations, but these are very rare. Generally, a spot is termed a 'giant' when it covers an area of 1500 millionths of the surface. A single spot with an area of 500 millionths is visible with the naked eye. While spots of a size covering up to 250 millionths comprise 86 per cent of the total, those rising to 1000 millionths represent only about 1 per cent and those larger than 2000 millionths no more than 0·2 per cent. The longest-lived spot recorded during the last 80 years lasted from 26th May until 11th November 1948. To this record of 170 days could be added a further 10 days representing the period of birth in the averted hemisphere, and the maximum area of the spot was roughly 2400 millionths. Large groups appear as long, complex swarms extending in longitude for more than 150,000 km; one of these, nearly 300,000 km in length, was seen during March 1926, in a region where there had been some activity for several months. And in February 1946 a large group with a maximum area of 5200 millionths appeared at latitude 26° north. The next largest had the record area of 6130 millionths. It appeared in April 1947, at latitude 24° south.

From fig. 5, it will be seen that the average daily relative number as computed at Zürich in 1957 gives R = 190·2: higher than any year since the time of Galileo, though records prior to 1749 are of doubtful accuracy. Similarly high relative numbers were observed in 1778 (R = 154) and 1947 (R = 152). From the shape of the curve covering the nineteen cycles, it will be seen that there is particularly marked activity every 70 to 100 years. A maximum for the nineteenth cycle was reached in 1957–8. By November 1956 solar activity was thought to have reached its maximum for the cycle, even though minimum had occurred only three years earlier (in 1954) and was unlikely to be surpassed. However, further increase became evident in the following June, and the rise went on during October, reaching a record level by November.

During this nineteenth cycle, R attained 300 for two days in 1956 and for a period of 11 days in 1957, while during the previous maximum of 1947–8 only four such days had been recorded. Almost equal values had occurred during the high maxima of 1778 and 1870, but the relative number of 355, reached on 24th and 25th December 1957, was an all-time record. Among the features of this extraordinary cycle was the appearance of a spot, on 21st June 1957, at a latitude of 50°·3 north, with an area of 50 millionths – apparently an exceptional group of pores of short lifetime, and at the highest latitude ever observed. The cycle was also remarkable for the fact that it had no spots of large dimensions such as had been seen during the eighteenth cycle, or in fact in all earlier cycles; the high relative number was due to the occurrence of a large number of small spots.

As we have seen, spot-groups are surrounded with zones varying in size and made brilliant by the presence of faculae. The zone covered by faculae is some 15° greater than that occupied by the spots, and extends in the direction of the

pole, so that the mean latitude of the faculae is rather greater than that of the spots themselves. During parts of a cycle, faculae are found at high latitudes. These 'polar faculae' make sporadic appearances, but were particularly notable at the end of the eighteenth and the beginning of the nineteenth cycle; their average diameter approached 2300 km, and their

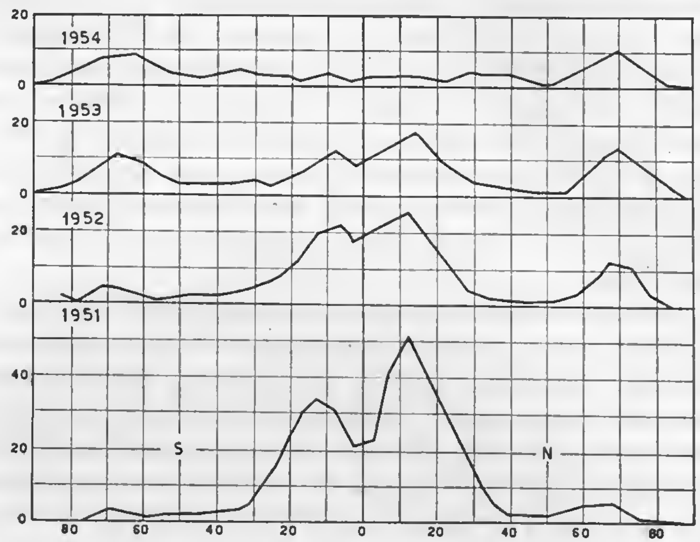


FIG. 8. Distribution of polar faculae, in latitude, from 1951 to 1954. (*Astr. Mitt.*, Zürich, No. 194.)

duration ranged between a few minutes and several days. The mean heliographic latitude of these polar faculae is about 66°, with an annual variation due to the inclination of the Sun's axis. At latitude 68° the faculae are dense, and fairly uniformly distributed, while at lower latitudes they are less common. A special characteristic is the formation in them of luminous points of great brilliance, and of diameters from 2″ to 5″; the brightest areas in the irregular structure of these faculae exceed the brightness of the surrounding photo-

sphere by 40 to 50 per cent. Investigations of the monochromatic radiation of the Sun help in an understanding of the phenomena associated with faculae. Polar faculae, first detected by Secchi, are circular in form, randomly scattered, and closely related to the general magnetic field (page 112) and to the polar rays of the corona. Fig. 8 shows the distribution of faculae in 1951–4, between the eighteenth and nineteenth cycles, when there was exceptional activity – another unusual aspect of the cycle which began in 1954. As the figure shows, the zone of the polar faculae was more active than the equatorial zone in 1954. Faculae appeared as high as latitudes 70° to 75° during this period, but all the polar faculae had disappeared by 1957.

Chapter III

OPTICAL INSTRUMENTS FOR INVESTIGATING THE SOLAR ATMOSPHERE

Early studies of the Sun were carried out by means of the telescope alone. This involved obvious limitations, and new methods have gradually been brought into use. Of these newer instruments, the most important are those associated with spectrum analysis.

In order to carry out detailed studies of the phenomena seen on the Sun's surface, a much larger image is required than is obtainable by the simple method of just projecting the solar image through the eyepiece and on to a screen, and if this image is to be as bright as possible and making use only of a telescope object-glass or parabolic mirror, an exceptionally long focal length is essential. In fact, since the Sun has a mean apparent diameter of 32′, a one-metre increase in focal length yields an increase of about 1 cm to the image at the focus of the object-glass or mirror. The object-glass must of course be achromatic, so as to reduce chromatic aberration as far as possible, so that nowadays there is a preference for the use of aluminized parabolic mirrors, which do not suffer from this defect.

As we have seen, in order to obtain a reasonable image, say of the order of 10–20 cm diameter, it is necessary to employ a telescope of long focal length. The best solution is to fix the

telescope in a horizontal or vertical position. The vertical design first put forward by Hale, at Mount Wilson, resulted in the 'solar tower'. Whether the telescope is erected in a horizontal or vertical position, a system of plane mirrors is used to maintain the Sun's rays in a fixed direction. Usually, this requirement is met by a main mirror termed a coelostat, mounted equatorially and driven so as to follow the Sun in its diurnal journey across the sky. A second fixed mirror is placed in such a way as to reflect the rays to the object-glass or mirror of the telescope, so that the telescope itself may be made to any suitable focal length.

At Mount Wilson there are two such towers. The first, of 60 ft (18 m) focal length, is a simple iron lattice; the second, of 150 ft (46 m), is also of ironwork, but is constructed in two parts, the inner supporting the optics and the outer serving to protect the instrument from the wind. Many other towers of various kinds have since been built in other parts of the world, including one at Arcetri, in Italy, made of reinforced concrete. However, the most important research in solar physics has been carried out with instruments which disperse the light of the visible and invisible spectrum into its various wavelengths. This is generally done by using prisms or gratings, suitably mounted.* The instruments are known by different names according to their construction and the uses to which they are put.

In its most elementary form, the *spectroscope* – i.e. collimator, prism or grating, and telescope – is used to examine the spectrum of a light source. If a photographic plate is used in place of the eyepiece, the instrument is a *spectrograph*, and is able to photograph the spectra.

A modified form of spectrograph, used to photograph a very limited region of wavelength – that is to say, a mono-

* Fuller details of the action of prisms and gratings can be found in Thackeray, op. cit.

chromatic radiation from the Sun – is the *spectroheliograph*. Invented and constructed by Hale in 1892, it has since been developed, modified and perfected, so that it has been able to provide a great deal of information about the outer layers of the Sun. It is basically similar to the spectroscope, but a slit – the 'second slit' – is substituted for the eyepiece. If the Sun's image is formed at the principal, or first slit, the second passes only a narrow region of the spectrum, corresponding in width to the slit itself. The dispersing component (prism, grating or both) is placed in position, and it is possible to bring one particular Fraunhofer line into coincidence with the second slit. The second slit can then be adjusted so that it passes only this particular line. It is obvious that weak lines are unsuitable, since they would not affect the photographic plate; but intense lines in the solar spectrum, such as hydrogen (in the Balmer series) and calcium, can be studied, so that the distribution of the hydrogen or calcium over the Sun's surface may be determined. For this purpose it is necessary to arrange matters so that the apparatus steadily follows the movement of the image, so that the light from different portions of the spectrum successively enters the slit of the spectroheliograph. For example, the Hα line may be produced on the photographic plate, yielding a photograph of the monochromatic radiation due to hydrogen which extends over the whole disk of the Sun.

The optical arrangement of a typical spectroheliograph is shown in fig. 9. S_1 and S_2 represent respectively the first and second slits, O_1 the collimating objective, O_2 the camera lens, R the mirror or grating, and P the prisms.

Many instruments, of various types, are now in use; a monochromatic image of the Sun's disk is focused on the photographic plate, either by moving the apparatus as a whole, or by keeping the apparatus steady and moving the optical train and photographic plate in their respective positions in front of the first and second slits. The well-known

Rumford spectroheliograph made by Hale for the 1-m (40-in.) refractor at the Yerkes Observatory is an example of this second type. It uses a prism or grating, or both together, and

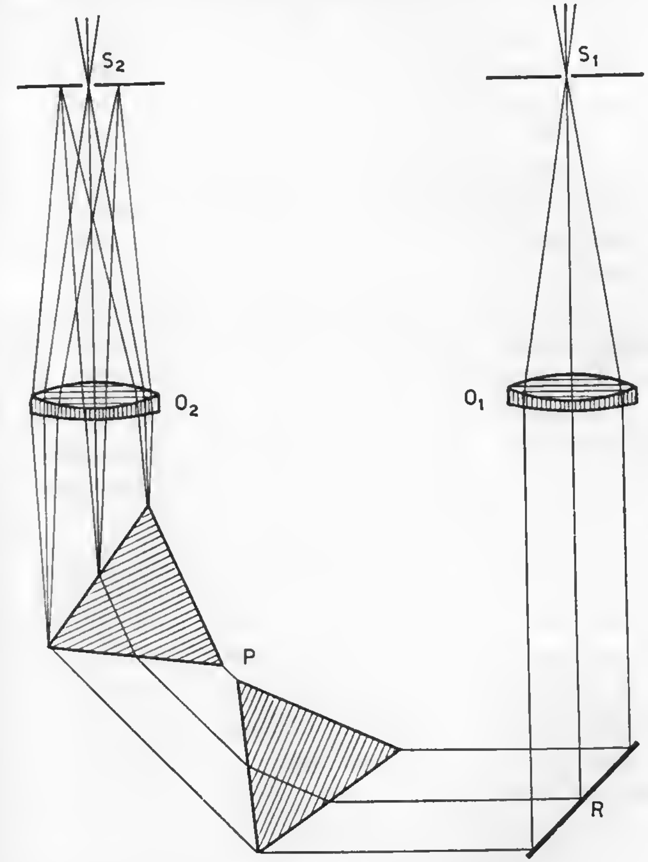


FIG. 9. Diagram of spectroheliograph.

over many years has provided a great deal of information by means of studying monochromatic radiations of the hydrogen and calcium.

Given that it may be both convenient and necessary to use

long focal lengths in such investigations, it is obvious that spectrographs and spectroheliographs used with horizontal or vertical telescopes should themselves be of the fixed type. At the Observatory of Meudon, in France, there is a *multiple spectroheliograph*, where the simultaneous movement of the objective (25-cm aperture and 4-m focal length) and the photographic plate is arranged by means of two synchronous electric motors. Four alternative combinations are possible using the same objective and collimator, so that different image-sizes and dispersions of the various Fraunhofer lines may be obtained by changing the optical train and the method of dispersion.

With solar towers, the spectrograph or spectroheliograph is usually placed in a shaft under the axis of the tower. At Arcetri, for example, these instruments are located in such a shaft, while the observations are carried out in a room at the base of the tower. The first and second slits are supported on a platform which can be rotated about its vertical axis, and also moved horizontally, with uniform motion, for an interval equal to the diameter of the solar image, which may be anything from 3 to 17 cm depending on the focal length of the objective used. An electric motor provides the translation motion to the spectroheliograph, in which a grating with 600 lines per millimetre is used. When the instrument is used as a spectrograph, the second slit is withdrawn, and is replaced by a slide containing a 9 × 36 cm photographic plate, recording an image of 36 cm length. The conversion takes only a matter of seconds, in each case making available a focal length of 4 m with an average dispersion on the plate, using the grating, of approximately 1 mm = 4 A.

The McGregor tower of the McMath-Hulbert Observatory, in Michigan (fig. 10), contains a type of monochromator fitted with electronic recording detectors specially constructed for intensity measurements in different regions of the

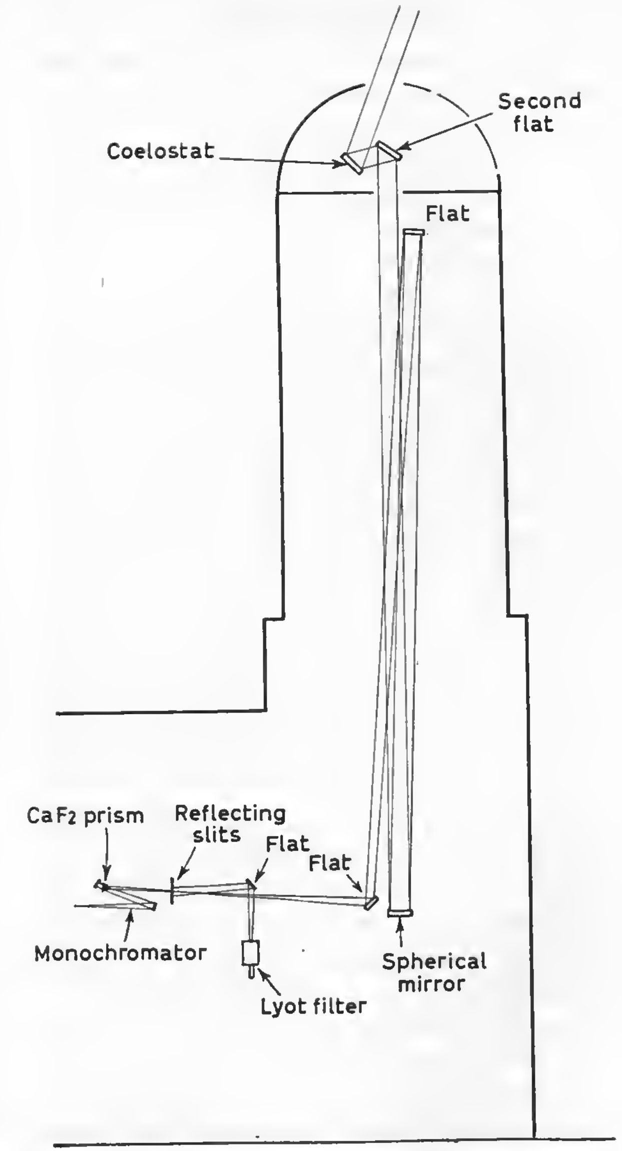


FIG. 10. Solar tower and monochromator at the McMath-Hulbert Observatory at the University of Michigan.

spectrum. The mirrors and collimator form an image at a focal distance of 6·7 m. As all the optics in the instrument are reflecting, it is achromatic, and so may be used for the whole of the spectral region. In the photographic and visual regions, high-sensitivity photo-emission cells are used as detectors; in the near infra-red, photo-emissive or photo-conductive cells are most useful, while in the far infra-red bolometers, thermocouples, or lead sulphide cells are employed.

During the last 40 years, spectroheliographs have increased our knowledge of solar physics beyond all recognition. The spectroheliograph has now, however, been to some extent superseded by the monochromatic filter which isolates Fraunhofer lines, invented in 1933 by the French astronomer Bernard Lyot. The principle on which the filter operates is by passing the light through a series of polarizers (P_1, P_2, P_3 . . .) having their planes of polarization parallel, and with interposed plates of quartz or Iceland spar (1, 2, 3 . . .) which have been cut parallel to the optical axis of the crystal. The surfaces of these plates are parallel, and normal to the rays of light; their optical axes are also parallel, and make an angle of 45° with the planes of polarization of the polarizers. Each of the plates is twice the thickness of the preceding one. The polarizer P_1, because of its polarizing action, only transmits half of the available light. The thickness of the quartz plates is calculated so that, for a given wavelength, the difference in the optical path between the ordinary and extraordinary rays is equal to a whole number of those wavelengths (this difference in the optical path is a function of the difference of the index of refraction for the ordinary and extraordinary rays; that is to say, of their different velocities in the crystal). For a given wavelength, the filter will transmit as a function of its thickness. The ordinary and extraordinary rays passing out of the quartz or spar strike the second polarizer P_2, oriented in the same way as P_1. As one plate has twice the thickness of the

other, the interference factor is doubled, until finally the chosen wavelength is isolated. Fig. 11, for example, illustrates a filter calculated to transmit the two lines 6370 and 6563 A. Iceland spar has the advantage over quartz of reducing the thickness of the plates by a factor of one-twentieth.

Temperature variations affect the thickness of the plates, and therefore their refractive index and the phase difference.

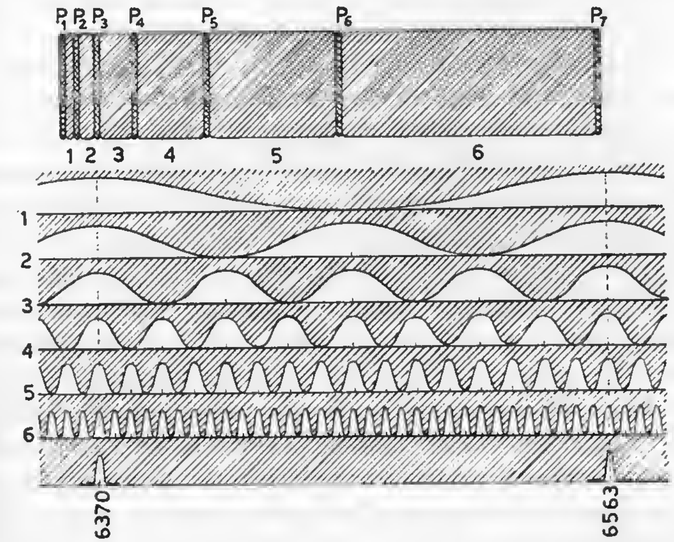


FIG. 11. Diagram of the Lyot monochromatic filter.

This results in a shift of the transmission band, so that in order to alter the wavelength passed by the filter it is necessary only to change the temperature. By this means it is possible to bring a particular transmission band into precise coincidence with the radiation to be isolated. As an example: between 10° and 60° C, the band transmitted by a quartz filter is shifted of about 30 A in the red to 22 A in the blue.

By means of this technique, Lyot designed various filters to isolate, for example, the Hα line and the green 5303 line

of the solar corona, within a band of less than 1 A. Such a filter could be made with six quartz plates and seven polarizers, joined by Canada balsam, and forming a parallelopiped with a rectangular base 150 mm long and 36 mm wide. The entire filter was contained in a thermostat, the temperature of which could be regulated as required. In 1941 Lyot added an optical train to the filter, and also a camera. He obtained film records of the green coronal line 5303 A, the red line 6374 A, and the Hα line at 6563 A.

Lyot also devised a type of standard monochromatic heliograph for use in observations to be carried out during the International Geophysical Year. Many of these instruments are now in use at various observatories. The apparatus consists of three separate optical trains. One is the monochromatic telescope, with a 14-cm objective and ratio f/10. The pencil of rays from this passes through two glass filters before entering the Lyot filter as a parallel beam. The temperature of this filter is thermostatically controlled, so that at the operating temperature (44·2° C) the band passing 0·7 A is kept fixed on the centre of the Hα line (6562·8 A). The pencil of monochromatic rays passing out of the filter forms an image, 15 mm in diameter, at the focus of the objective. Also, as part of this first optical system, there is an eyepiece conveniently positioned at the side of the camera. This allows visual inspection of the image to be made during intervals between the exposures.

The second optical train is concerned with the electronic and photometric guidance system. The equatorial mounting of the heliograph enables the Sun to be followed as it moves across the sky, the electronic guidance system with its photocells maintaining the image in the centre of the field to within an accuracy of 1″ to 2″. The third optical system serves two purposes: first to record, on the film, a clock showing universal time; secondly, to record a photometric calibration

showing different degrees of intensity. The quality of the light marking this calibration on the film is the same as that forming the solar image, while the time of exposure is the same whatever may be the transparency of the atmosphere. The instrument is particularly suited to following continuous-changing phenomena on the Sun and for studying their characteristics, especially with regard to intensity, which is recorded with great accuracy by the system of photometric calibration.

It will be appreciated that the interference filter has many advantages compared with the spectroheliograph. It enables a complete picture of a region of the Sun to be obtained without the need for integrating many successive observations; moreover, cinematograph records have been obtained by means of the filter, and have already provided important information about the movements of the gases overlaying the solar surface.

Another most important instrument, also due to the genius of Lyot, is the *coronagraph*. As the name suggests, it is used for studies of the Sun's corona. Since the corona is much less brilliant than the photosphere, it cannot be seen in full sunlight; there is too much scattered light coming from the intensely bright surface of the Sun. At a distance of 1′ from the Sun's limb, the halo of light diffused around it is usually of the order of one thousandth of the brightness of the disk, while in white light the brightness of the corona is only one or two thousandths. By means of spectrographs and filters, many attempts have been made over the years to see the corona, or to photograph it – usually from the tops of mountains – but without success. In 1930, however, Lyot used his coronagraph to photograph the inner corona and the more intense lines of its spectrum in full sunlight. He achieved this by doing everything possible to reduce the amount of light diffused by the halo. A special optical arrangement was used, and the observations were carried out at a considerable height

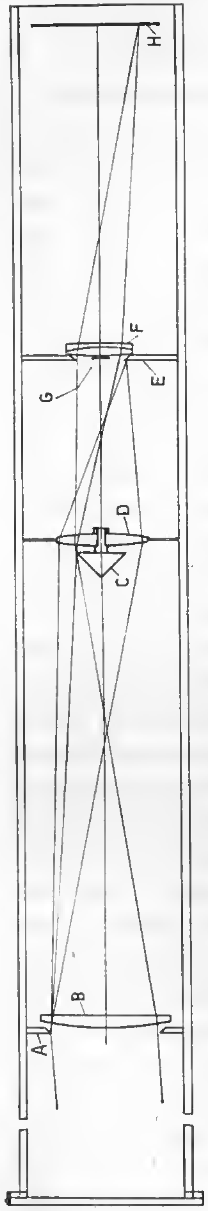


FIG. 12. Diagram of Lyot coronagraph (J. W. Evans).

above sea-level, high above the region where dust collects in the lower layers of the Earth's atmosphere.

It is essential to eliminate every imperfection in the glass used for the objective – air-bubbles, striations, scratches – as well as flaws in the other optical parts, diffraction effects at the surfaces and multiple reflections at the objective. Thus the coronagraph comprises an object, B, of a type different from the achromatic astronomical object-glass; it is a simple crownborosilicate lens, so that there are only two surfaces instead of the usual four. The coronagraph at the Pic du Midi has a lens of 400 cm focal length, with an aperture of 20 cm; the instruments at Climax (Colorado) and Sacramento Peak (New Mexico) are of 40 cm aperture. A small metal cone reflector C (fig. 12), slightly larger in diameter than the solar image, is placed in the focal plane of the objective in order to hide the Sun's disk, and to reflect its light and heat out of the telescope tube. A field lens D, to which is fixed the small cone C, gives an image of the objective A on the diaphragm at E. The diameter of this diaphragm is just smaller than the image of the bright ring produced by the light diffracted at the objective, A, which intercepts it. Behind E is a second objective F, which forms an image of the shielding disk and the corona surrounding it at H. At the centre of the lens F is a small

dark spot G, which intercepts the small image of the Sun formed by the double reflection from the surfaces of the objective, and which is brought to a focus on G by the field lens. The telescope tube carries a long extension at the front to protect the lens from humidity and dust, which is trapped by a layer of grease rubbed around the inside of the tube. The efficiency of the whole instruments depends greatly on the quality as well as the cleanness of the objective lens – under the best possible conditions, the luminosity of the instrumental halo is of the order of 5 millionths of the incident light – and on the transparency of the atmosphere at the site chosen for the observations.

Using an instrument of this kind – to which, incidentally, a spectrograph may be added to study the spectrum of the corona – Lyot was the first to observe and photograph the inner corona in broad sunlight. He carried out his work from the Pic du Midi Observatory, at an altitude of 2870 m. Subsequently, the coronagraph came into wide use at other observatories – notably at Arosa (a department of the Zürich Observatory), in the United States, in Russia and in Japan. However, the coronagraph has not affected the importance of observations made during total eclipses, to be described later. For eclipse work it is necessary to use apparatus which is portable and, to some extent, makeshift: long-focus cameras, horizontally mounted and using filters and different types of photographic emulsions, as well as cinematographic apparatus with long-focus lenses in order to cover the various phases of the eclipse.

An important contribution to the study of solar radiations has recently been made by rockets and artificial satellites. This applies particularly to the radiations which are blocked or absorbed by the upper layers of the Earth's atmosphere. Since 1946, vehicles of various types have been sent up from the United States, equipped with spectrographs to make auto-

matic exposures during flight. Devices to increase the useful range of the spectrograph have been produced, and spectrograms may be obtained at the moment when the rocket reaches its greatest altitude above the Earth's surface. The instrumentation is then released by parachute, and subsequently recovered. Much new information about the ultra-violet spectrum has already been obtained (pages 61 and 62).

Many instruments, making up a veritable astrophysical laboratory, are needed for detailed studies of the Sun. Laboratory spectrographs of various designs are used to compare spectra of elements such as iron, sodium and hydrogen with their spectral lines as given by the Sun. Micrometer comparators of high precision are employed to measure the wavelengths of spectral lines, while micro-photometers with thermopiles or photocells measure the amount of blackening of photographic emulsions produced by the effect of the light-rays to which they have been subjected. The actual intensity of the light from different phenomena which has been recorded on the photographic plate is determined from readings given by the instruments and taking into account the calibration curves of the particular emulsion used.

Chapter IV

THE SPECTRUM OF THE SUN AND THE PHOTOSPHERE

Solar radiation extends from the shortest wavelengths – the very short γ-rays – through Röntgen or X-rays to the ultra-violet. This radiation ionizes the gases in the Earth's atmosphere through which it passes, and by which it is completely absorbed long before it can reach the surface of the Earth. At about 2900 A, ultra-violet radiation begins to reach the Earth, followed by the rays of the visible spectrum, extending to approximately 7000 A, and then through the infra-red into the region of radio waves of length measured in centimetres or metres. The possibility of exploring the whole of this spectrum is now being realized, through the development of new techniques and special photographic emulsions, new dispersive media to supplement glass, the use of photoelectric cells, and the development of rockets capable of passing out of the Earth's atmosphere.

That portion of the spectrum which may be investigated visually, or (better) photographically, covers the continuous band of light from the ultra-violet to the infra-red. In this we see absorption lines (Fraunhofer lines) of varying density and width.

In 1946 it became possible to photograph the spectrum up to 2100 A, using rockets reaching to an altitude of some 200 km, and it was found that there were many lines which could not be resolved; they appeared to be multiples of Fe^{I}

and Fe^{II}.* The resonance lines Mg^{II} at 2802·7 A and 2795 A were very noticeable; their absorption covered a band of 50 A with extended edges. At the centre of each absorption line a thin emission line was seen. Moreover, it was possible to investigate higher frequencies, up to the Lyman region (1216 A) – the intense hydrogen emission line. By indirect methods, not spectrographic in nature, other lines of strongly ionized atoms were found, such as He^{II}, C^{II}, C^{III}, Si^{II} and up to Si^{IV}. From these results, it was evident that the emission came from the higher layers of the chromosphere or from the corona, where the temperature increased rapidly with increasing distance from the bright body of the Sun. Other investigations have been made into the spectrum as far as 800 A, confirming that the energy emitted in this region is similar to that from a black body at a temperature of 6000° K. X-rays of wavelength less than 7 A or 8 A have also been identified during solar disturbances, but they are weak, and are absorbed in passing through the ionospheric E-region of the Earth's atmosphere.

In 1896 H. Rowland, by means of his well-known concave grating, photographed the solar spectrum from 2980 A to 7330 A, and published a volume containing 20,027 lines with wavelengths up to a million Angströms, together with their intensities, calculated empirically, and – where possible – their chemical identity. A complete revision of Rowland's atlas was undertaken by the Mount Wilson Observatory in 1928. This included 21,835 lines from 2975 A to 10,218 A, with intensities on the same scale as Rowland's, identification of the elements, the temperature, pressure and the excitation potential. This list was further extended to 13,495 A by H. Babcock and C. Moore, and subsequently the Utrecht Observatory published a photometric atlas of the solar spectrum.

* Fe^{I} denotes a neutral Fe atom, and Fe^{II} an atom ionized by the loss of an electron.

By means of a special microphotometer, the precise intensities of the Fraunhofer lines from 3332 A to 8771 A were established, and reproduced in a series of diagrams, showing the amount of absorption of the various lines in this region. These diagrams are drawn to a scale of 2 mm/A, enabling the wavelength to be read to an accuracy of 0·01 A. Similar atlases compiled by the Uccle and McMath-Hulbert Observatories have extended our knowledge of the solar spectrum to the far infra-red, at 25,242 A.

In the table given here, a list is provided of some of the lines, with the designation given at the time of discovery, the identification, and the wavelength.

THE BRIGHTEST FRAUNHOFER LINES IN THE VISIBLE SPECTRUM

Letter	*Wavelength in Angströms*	*Identification*	
A	7593	O_2	Telluric
a	7183	H_2O	Telluric
B	6867	O_2	Telluric
C(Hα)	6563	H	Solar
D_1	5896	Na	Solar
D_2	5890	Na	Solar
E	5270	Ca, Fe	Solar
E	5269	Fe	Solar
b_1	5183	Mg	Solar
b_2	5173	Mg	Solar
b_3	5169	Fe	Solar
b_4	5167	Mg	Solar
F(Hβ)	4861	H	Solar
f(Hγ)	4340	H	Solar
G	4308	Fe, Ti	Solar
g	4227	Ca	Solar
h(Hδ)	4102	H	Solar
H	3967	Ca^{II}	Solar
K	3933	Ca^{II}	Solar

Lines are identified by comparison with laboratory determinations of wavelength and intensity. There are many lines of Fe^{I} scattered throughout both the solar and the laboratory

spectra, and for this reason they have been chosen as the wavelength standard for measurement; the International Angström (I.A.), generally accepted as the unit of wavelength, is referred to the red line of cadmium (Cd) at 6438·4696 A. Most of the elements found on the Earth also exist in the Sun; and from detailed investigations of the Fraunhofer lines, quantitative and qualitative analyses have been carried out. In the Sun, the elements H, Na, Mg, Si and Fe are abundant; Ti, V and Cu are also present; Ag is rare. The temperatures at which these lines first appear have been tabulated. Lines which are the most persistent, and which are produced with minimum excitation, are termed ultimate lines.

The significance of this behaviour of atoms may be explained by the theory of ionization and by the quantum theory.* The ultimate lines are absorbed from atoms in their lowest state of energy. As the excitation is increased, so the absorption reaches a higher state or level, in which the energy is greater. Consequently the atom loses one or more of its outer electrons, and passes from the first spectrum to another which exhibits new lines differing from those produced by the neutral atom. Transitions from one complete stage to another produce groups of lines known as *multiplets*, which may be regarded as units, and can be used as a means of identifying the element responsible for them.

The term 'excitation potential' used in respect of a given line is the energy, expressed in electron volts,† required to raise an atom from its lowest energy level to the state in which it is able to absorb the line. For ultimate lines this quantity is zero, or certainly very small. Also used in this connexion is the term 'ionization potential', a measure of the energy re-

* For fuller details, see Thackeray, op. cit.

† An electron volt (eV) = $1{\cdot}6030 \times 10^{-12}$ erg; it is the energy absorbed by an electron accelerated through a potential difference of 1 volt.

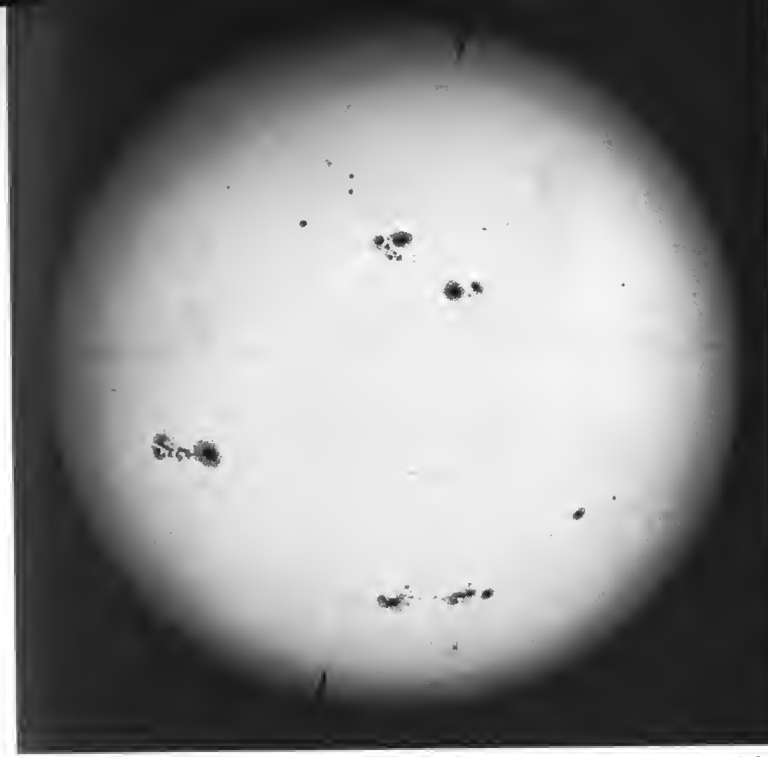
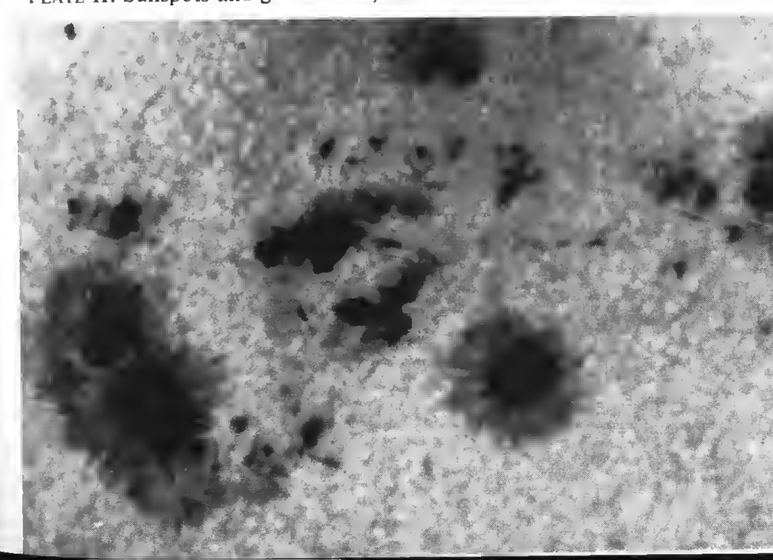


PLATE I. Direct photograph of the Sun, 21st July 1957. (United States Naval Observatory, Washington, D.C.) The upper index shows the north pole; the lower, the south pole. The group of sunspots in the southern hemisphere is prominent; this was exceptional in view of its high latitude (about 40° S.), its duration and its appearance, bearing in mind that it occurred near a solar maximum.

PLATE II. Sunspots and granulation, 21st October 1958 (Fraunhofer Institut).



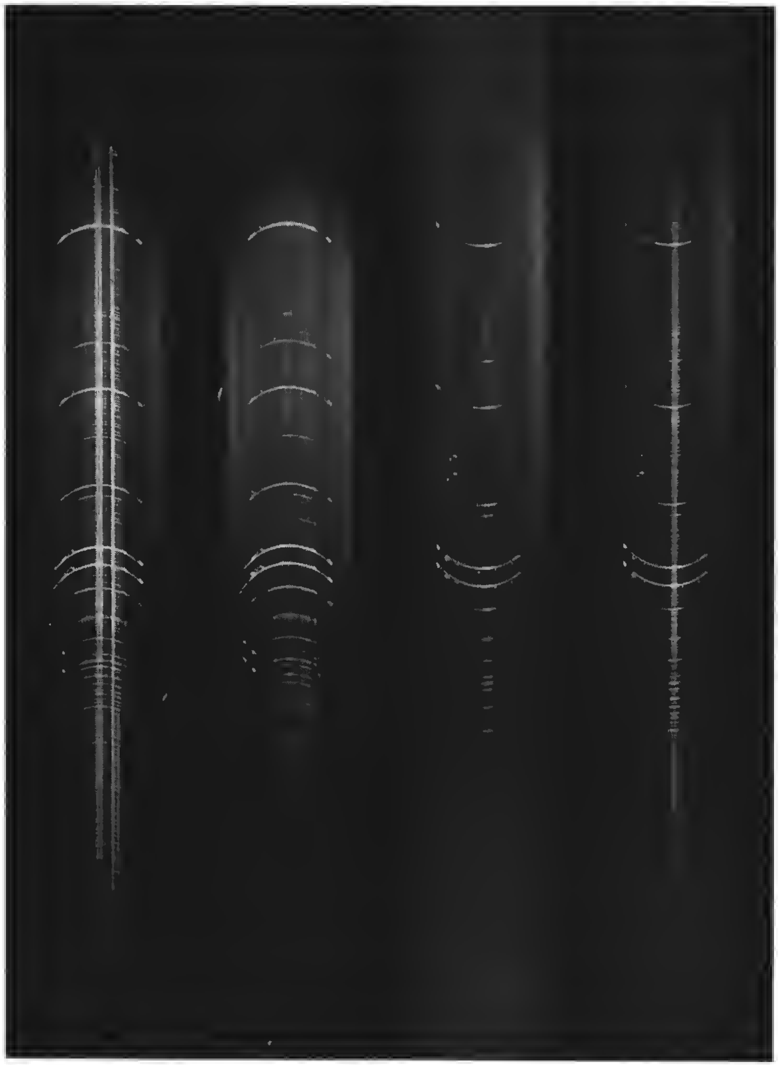


PLATE III. Flash spectrum photographed by the Lick Observatory expedition to the eclipse of 31st August 1932.

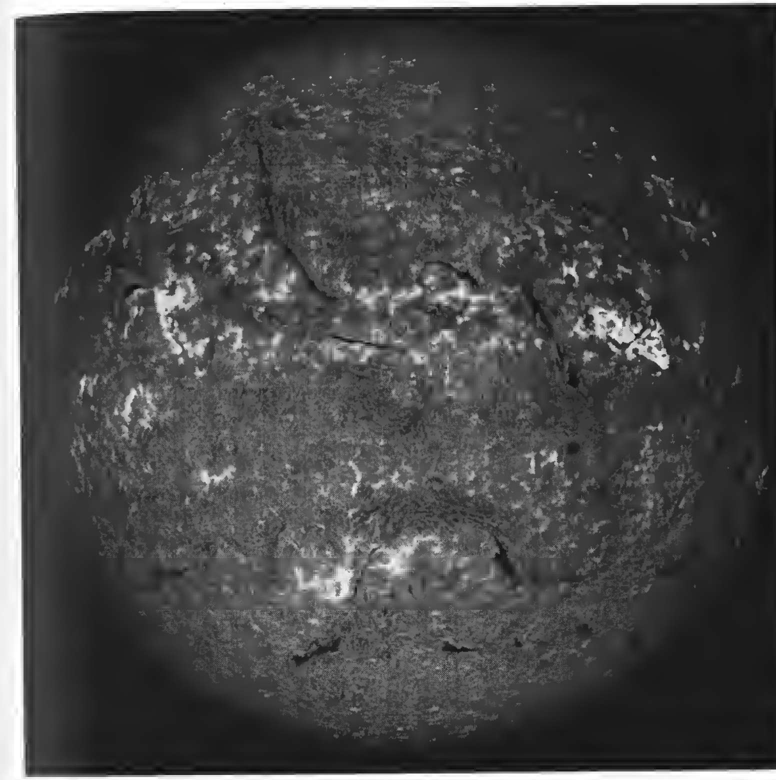


PLATE IV. Monochromatic photograph in the Hα line, 7th July 1959, $8^h\ 30^m$ U.T.

PLATE V. Monochromatic photograph in the K_3 line, 7th July 1959, $10^h\ 4^m$ U.T. (Arcetri Solar Tower).

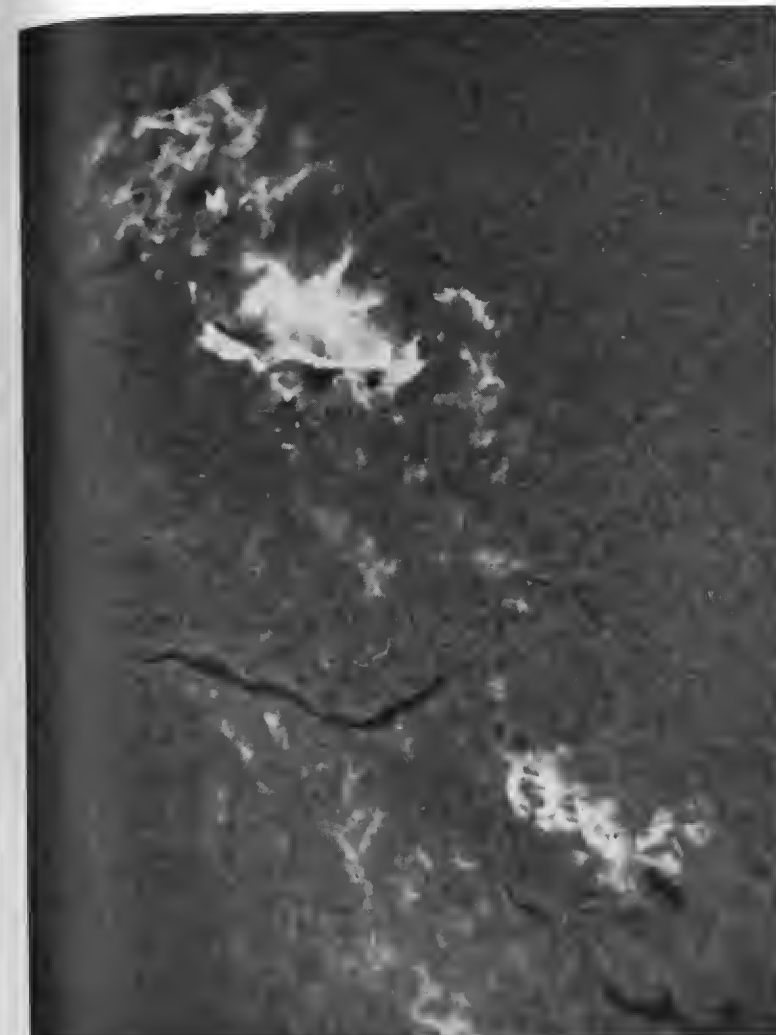


PLATE VI. Flare of magnitude 3, photographed in Hα light on 7th November 1956, $12^h\ 19^m$ U.T., at the Anacapri station of the Fraunhofer Institut.

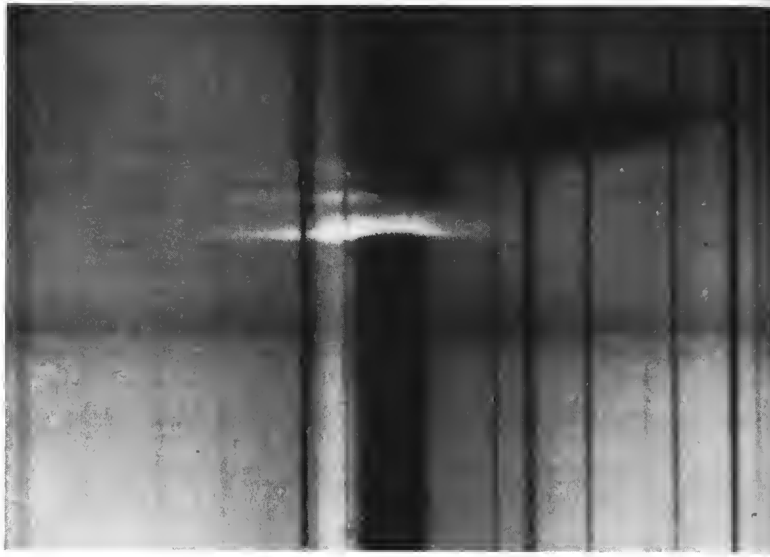


PLATE VII. Flare on the Hα line (Fraunhofer Institut, Anacapri).

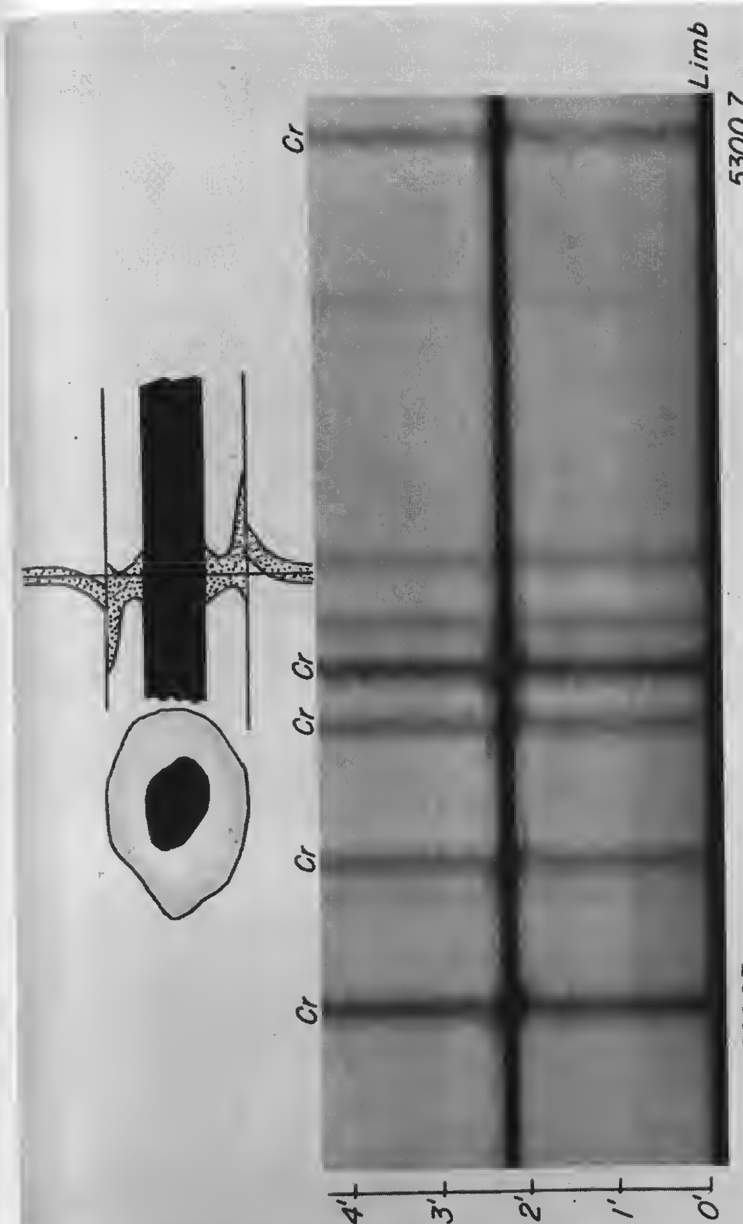


PLATE VIII. Evershed Effect in a group of intense lines of chromium (Cr). (O. Mohler, McMath-Hulbert Observatory of the University of Michigan).

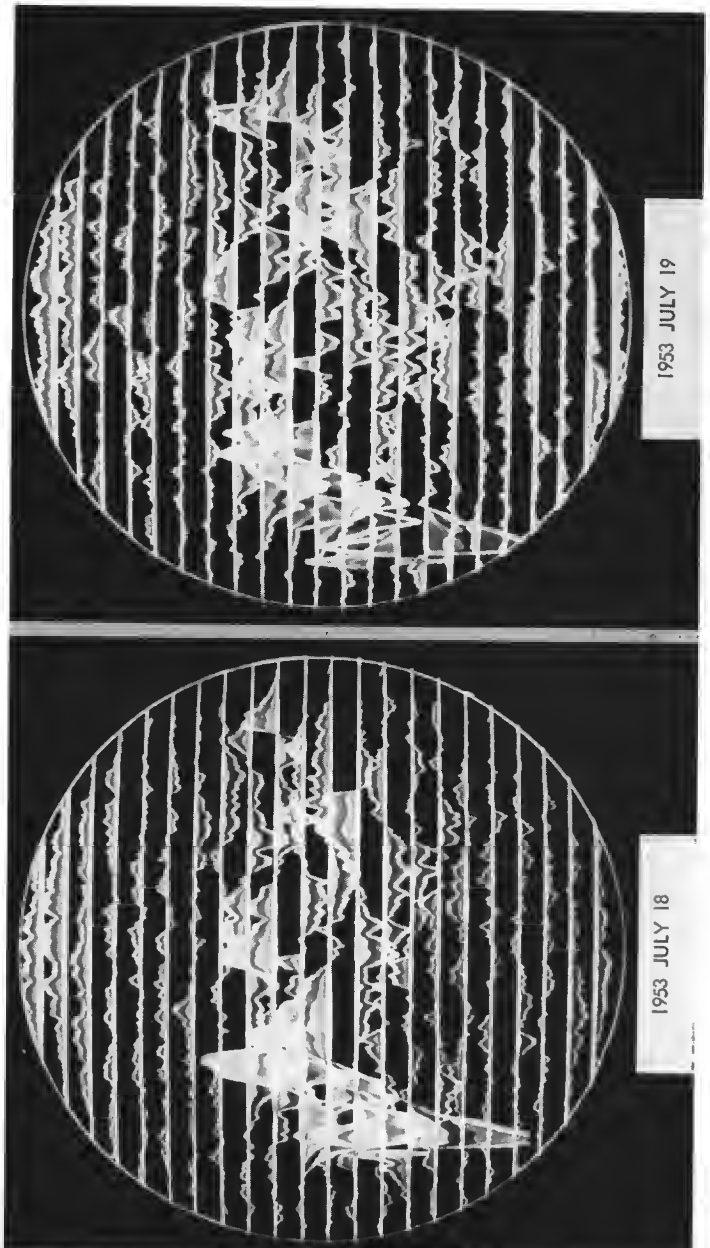


PLATE IX. Solar magnetograms (Mount Wilson Observatory; H. W. and H. D. Babcock).

quired to remove an electron from the atom, and usually measured in electron volts.

Of all the elements present on the Earth, some sixty are known with certainty to occur also in the Sun. Among those about which some doubt exists, and those which are certainly absent, it is possible to recognize three groups; (1) some of the rare-earth elements; (ii) gases such as F, Kr, Ne and Xe – because the most important lines of this group are in the ultra-violet region, and are consequently absorbed by our own atmosphere, while other lines of these elements appearing in more accessible regions of the spectrum require a much greater degree of excitation than is present in the photosphere; (iii) heavy elements with an atomic number greater than that of gold (79); probably such elements exist in the Sun in amounts too small to produce lines of sufficient intensity to be detectable.

Most of the Fraunhofer lines originate in the Sun's atmosphere, while a smaller number of lines is attributed to absorption in the atmosphere of the Earth. These latter are known as *telluric lines.* If we examine the solar spectrum, from an observing site high above sea-level, first when the Sun is near the zenith and then when the Sun is low over the horizon, we find that there are many lines in the second spectrum which are not present in the first, while intensity differences may also be detected. In the case of the low Sun, the rays come through a greater depth of atmosphere, and the effects of terrestrial absorption are increased, so that comparison of the two spectra betrays the lines of telluric origin. Further confirmation of the origin of these lines is provided by observing the Doppler effect at the eastern and western limbs of the Sun. Solar lines are subject to the Doppler shift due to the Sun's rotation, while telluric lines are not, and so appear stationary.

Telluric lines are due to oxygen, ozone, carbon dioxide

(CO_2) and water vapour (H_2O). In the ultra-violet region Fabry and Buisson discovered lines between 2900 A and 3150 A caused by a layer of ozone at an atmospheric pressure of 3 mm, which varied with time; this layer appeared to be approximately 40 km above the surface of the Earth. In order to explain the existence of this layer, Fabry and Buisson suggested that the ozone was produced by ultra-violet radiation from the Sun, at about 2000 A, which penetrated only the outer layers of the Earth's atmosphere; radiation of greater wavelength caused dissociation of the ozone, preventing concentration beyond the amount needed to establish equilibrium.

As we have seen, the spectrum of the photosphere is of type G0 on Draper's system of classification. Most of the lines are due to the atoms of different elements, enhanced lines being weaker than those of the preceding class, while the arc lines are more intense. The H and K lines due to Ca^{II} and the band G are very marked. $H\gamma$ is half the intensity of Fe 4326 A; the blend line of Fe and Sr at 4077 A, and the $H\delta$ line of Ca^{I} at 4227 A, are of almost equal intensity. The continuous spectrum is of almost constant intensity between $H\beta$ and $H\varepsilon$. Excitation potentials are low for most of the lines; an average value for many thousands of metallic arc lines is only slightly more than one electron volt, with the highest value, that for Pb, at 5·8 eV. On the other hand, non-metallic lines have much higher excitation potentials – but they are rare and, with the exception of hydrogen, are very much weaker. Data are given in the table on page 67.

In addition to atomic lines, the spectrum of the photosphere – as well as the spectra of sunspots – contains many bands due to molecules. The following chemical compounds have so far been identified: CN, C_2, CH, NH, OH, CaH, MgH, AlH, SiH, H_2, SiF, BO, AlO, TiO, FeO and ZrO. All these are unstable on the Earth.

While the spectrum of the photosphere in undisturbed regions is constant, with no variations of lines or of the continuous spectrum, changes do occur in the disturbed regions, because of the greater emission from faculae and lesser emission from sunspots. Another change takes place throughout the whole spectrum in moving from the centre of the Sun's disk toward the limb. Three distinct effects are seen when the spectrum near the limb is examined, and these differences are of great importance in the theoretical study of the Sun's constitution.

The more intense lines of the spectrum are accompanied

AVERAGE EXCITATION POTENTIALS FOR NON-METALLIC LINES

Element	*Average Excitation Potential in eV*	*Maximum Intensity*	*Number of Lines*
He	20·9	0	1
H	11·1	40	6
N	10·0	−2	1
O	9·3	2	5
C	7·5	0	9
S	6·5	−1	3

by the appearance of the so-called 'wings', i.e. a gradually increasing absorption of the spectrum in the vicinity of the lines. These wings become much weaker near the limb of the Sun's disk, and in some cases disappear entirely. At the same time there is a gradual slight broadening of all the lines, and, with most of them, a considerable intensity-change; some become stronger, others weaker. These differences in relative intensity are not noticeable in the less refractive regions of the spectrum, except in the cases of those lines with wings – such as those of the elements Na and Mg. In such cases the wings are not greatly reduced in intensity near the limb, and the centre of the line is enhanced. In the region lying between 3815 A and 3840 A, the appearance of the spectrum does not

alter much from the centre to the limb; the wings, so characteristic at first, have almost completely vanished. This effect is due to the variation in the depth of the layer through which the radiation has to pass as one moves from the centre toward the limb. Temperature and pressure gradients bring about a change in the relative intensities of the lines; the reverse happens in the case of sunspots. Similar differences are found with regard to spectra of the stars.

Observation and theory combined have helped to clear up many of the problems associated with the origin of the Fraunhofer lines and the continuous spectrum. The chief source of opacity, at visible wavelengths in the Sun's atmosphere has its origin in the presence of one particular gas found in its atmosphere and some of the stars – negative hydrogen (H^-). By this is meant a hydrogen atom which has captured a second electron. In millions of atoms of ordinary hydrogen there is perhaps one negative atom. The emission or absorption noted each time an atom captures or loses an electron influences the appearance of the continuous spectrum, and also gives an indication of the colour of the gas making up the Sun's atmosphere. The main constituent is this negative hydrogen, never found on the Earth, and discovered only during studies of the Sun; its optical properties have been calculated theoretically.

The intensity of an absorption line is a measure of the amount of energy subtracted from the continuous spectrum. After the first empirical estimates made by Kirchhoff, Rowland and others, more precise measurements were carried out based on the 'equivalent width' for many lines, determined at various observatories. This unit is expressed in Angströms; a line having a width equivalent to 1 A is said to absorb an amount of radiation equal to that of 1 A in the continuous spectrum. The constant intensity of the Fraunhofer lines in the solar spectrum is of great importance, since it enables

quantitative chemical analysis of the Sun's constitution to be carried out.

Actually, the intensity of a spectral line is dependent on the abundance of the element responsible for it, on the number of atoms in an ionized condition, and also on the degree of excitation. Moreover, the number of atoms is related to the temperature and to the density of the free electrons present in the atmosphere. Consequently, the intensity of the line will depend not only on the quantity of the element, but also on the temperature and electron density in the atmosphere. Following the determinations of equivalent widths of lines, it has become evident that hydrogen atoms predominate not only over atoms due to metals, but also over those of the light elements. Most of the metallic atoms are ionized, while a small percentage shows a state of excitation.

All Fraunhofer lines have appreciable width. They extract energy from the spectrum along a region which may extend from fractions of an Angström for the weakest lines up to several Angströms in the case of the more intense lines, such as, for example, the Balmer series for hydrogen or the H and K lines of ionized calcium. In the case of metallic lines, the broadening of lines is due to two causes: damping, and the Doppler effect. All the atoms in the Sun are, naturally, in a condition of strong thermal agitation, so that an absorption line is produced by atoms at different distances from the terrestrial observer. Moreover, the towards-or-away movements – or radial velocities – are different for different atoms. Because of the Doppler effect, all these atoms have a varying degree of absorption, at frequencies slightly different from those of atoms which are at rest relative to the observer. The total effect of the many millions of atoms involved is to cause a broadening of the line.

Furthermore, every atom may be considered as a resonator at particular wavelengths, emitting or absorbing weak waves

either because of the natural damping, which the radiation undergoes due to passing among this atom and its neighbours, or to the effect of interaction between excited atoms and nearby particles, or to the effect of collisions. A line which is not weakened by these processes, should lie in one wavelength only and so should be infinitely narrow; however, the greater the degree of damping, the broader the resultant line. The most important cause of broadening in the cases of the lighter elements, such as hydrogen and helium, is the *Stark Effect*, which is due to the strong disturbing influence of a changing electric field caused by ions and free electrons being present. This disturbing influence is particularly strong in its effect on hydrogen atoms, and the wide arms of the Balmer lines are due almost entirely to the Stark effect.

Determinations of the profiles and equivalent widths of lines have established the existence of a relationship between pressure and temperature in the layers of the photosphere. This has to be taken into account if we want to obtain some idea of the amounts of each of the various elements present in the photosphere. To begin with it is necessary, then, to determine the number of absorbing atoms, remembering that Fraunhofer lines are subject to the Doppler effect, to turbulence of the gases in which they lie, and to damping. Use of theory shows that as the number of atoms increases, there is at first a rapid increase in the intensity of the line, until saturation is reached at a certain point where the intensity remains constant. With a further increase in the number of atoms, the intensity again starts to rise. From this, a 'growth curve' may be obtained, showing the number of atoms as a function of the equivalent width of the line. Because of the high temperature of the Sun, most of the metals are ionized, so that the effect of ionization on line intensity must be taken into account in any determination of the total number of atoms present.

Now the process of ionization may be expressed as follows: Atom + ionization energy → ions + electrons. Hence from data about the concentration of neutral atoms, ions and electrons, and applying chemical equilibrium theory and the quantum theory, a general formula which expresses the degree of ionization as a function of the electron pressure and the temperature can be evolved, as has been done by Megh Nad Saha.*

Each line of the spectrum for which the probability of transition is known gives a value for the amount of the element producing it – that is to say, the total number of atoms and ions in the various levels. This sum total is proportional to the abundance of the element. According to the results of various investigators, the abundance of elements present in the photosphere, expressed as the logarithm of the number of the particles, is: H = 12, He = 11, C = 8, N = 9, O = 9, Na = 6, Mg = 7·5, Al = 6, Si = 7, Ca = 6, Fe = 7 and Ni = 6. It may therefore be concluded that while the lighter gases found on the Sun are in different proportions from those on the Earth, the heavy elements, with an atomic weight

* Saha's formula is expressed as a logarithm to the base 10, with numerical values for the universal constant introduced as follows:

$$\log (P_e - x) = \log \left(\frac{g_j}{g_o}.2\right) + 2{\cdot}5 \log T - \chi_j \frac{5040}{T} - 0{\cdot}48$$

where P_e is the electronic pressure in *bar* (1 *bar* = 10^6 dynes/cm²), x the degree of ionization (ions/neutral atoms = x); g_j, g_o, $g_e = 2$, the statistical weights respectively of ions, neutral atoms, and free electrons – that is to say, the number of the simple quantum states in which a term is divided; χ_j the ionization potential in electron volts.

Assuming T = 5700 for the photosphere and P_e = 100 *bar*, Saha's formula applied to the Sun is as follows:

$$\log x = \log \left(\frac{g_j}{g_o}.2\right) - 0{\cdot}885\chi_j + 6{\cdot}91$$

This equation shows that the degree of ionization increases with increasing temperatures, and diminishes with the ionization potential and pressure.

greater than 20, are in the same proportion as in the Earth's crust and in meteorites. This may be explained by assuming that in a very early stage of the Earth's history the lighter elements were thrown off, as the terrestrial gravitational field was too weak to retain them. Qualitative analyses of the chemical composition of these compounds have been carried out, showing a preponderance of free radicals (CH, NH, OH) and confirming the abundance of hydrogen. The total mass of these compounds compared to the total mass of the atoms is very small – about 1000 times less than in the case of the metals, which is itself very slight.

Chapter V

TOTAL ECLIPSES OF THE SUN

The importance attached to the phenomenon of a total eclipse of the Sun is easy to understand when it is borne in mind that during the moments immediately before and after totality, it is possible to carry out direct observations of that part of the solar atmosphere known as the *chromosphere*. For a brief period only, while the brilliant photosphere is not visible, the chromosphere can be seen. And when the Moon has completely covered the Sun's disk, the *corona* may be seen extending outwards to a considerable distance; the outer part being available for study only during totality. It is, of course, true that Lyot's invention of the coronagraph has to some extent lessened the importance of eclipse work; as has been described, the instrument depends upon producing a kind of artificial eclipse by means of an opaque screen, so that the chromosphere and the inner corona may be studied in full sunlight – but with it the outer corona still cannot be seen.

If the Moon moved round the Earth in the plane of the ecliptic, solar and lunar eclipses would occur every month. In fact, as the plane of the Moon's orbit is inclined at an angle of 5° 8′ to the ecliptic, eclipses can occur only when the three bodies are in the same plane – that is to say, when the two orbital planes intersect along the line of the nodes. When the cone of shadow thrown into space by the Moon reaches the surface of the Earth, a solar eclipse takes place, but totality is visible only along a narrow belt. An eclipse is total only

when the Moon is reasonably near its perigee, or closest approach to the Earth. If the shadow strikes the Earth perpendicularly, its maximum diameter on the surface is 270 km. If the shadow falls obliquely, then totality occurs over an elliptical zone, the longer diameter of which is at maximum 270 km. Due to the effect of the combined motions of the Earth and the Moon, the shadow moves across the Earth's surface from west to east, with a velocity of about 365 metres per second at the terrestrial equator; at higher latitudes the relative velocity is, naturally, greater. Under the most favourable possible conditions, the maximum duration of totality in a zone near the equator is 7 minutes 40 seconds, while the maximum excess of the apparent semi-diameter of the Moon over that of the Sun is 1′ 19″.

Owing to the retrogression of the lunar nodes along the ecliptic, taking about 18 years to complete a full revolution, solar and lunar eclipses recur after this interval which corresponds to 223 lunations. The Chaldaeans named this period the *Saros*. The only major difference between one eclipse and its return at the next Saros is in the position of the zone on the Earth where the eclipse is total. In point of fact, total eclipses are by no means rare; on the average, there is one every 18 months. However, the limited zones in which each eclipse is visible show shifts in position from Saros to Saros, so that it takes 360 years for a really precise recurrence of any particular eclipse.

Astronomers have always been very ready to dispatch fully-equipped expeditions to study total eclipses of which various important factors associated with them may be calculated well in advance. Thus the four contact points – the first contact of the solar and lunar disks at the start of the eclipse, the second internal contact at the beginning of totality, the third contact when the Moon uncovers the first part of the solar disk, and finally the fourth contact when the Moon leaves the

Sun's disk completely – can be determined long before the expedition takes place and preparations made accordingly.

There are numerous observations which may be made during the brief period of totality. These may be summarized as follows:

(1) Observations to establish the relative positions of the Sun and Moon, in order to correct almanac tables.

(2) Photographic observations of the sky in the region of the Sun, so as to determine the apparent displacements of stars due to the 'bending' of light in the Sun's gravitational field (Einstein effect).

(3) Photographs of the corona and prominences.

(4) Spectroscopic examination of the so-called 'flash' spectrum – the spectrum of the chromosphere as it 'flashes' momentarily into view (see page 78) – as well as the chromosphere and the corona.

(5) Photometric measurements of the corona; also polarization measures.

(6) Bolometric measurements of radiation from the corona.

(7) Observations carried out with radio telescopes.

The results of these various programmes will be considered below. First, let us deal briefly with those results so far achieved under heading (2).

Astronomical Proof of the Theory of Relativity

Great interest has always been shown in the so-called astronomical proofs of the theory of relativity.* As far as the Sun is concerned, there are two relevant observations: the shifts of lines in the solar spectrum toward the red, and the 'bending' of light-rays from remote stars owing to the influence of the Sun's gravitational field.

The first of these, commonly known as the 'Einstein effect',

* A discussion of relativity theory is to be found in *Fact and Theory in Cosmology* by G. C. McVittie, also in this series.

has given decisive results when applied (by W. S. Adams) to the line-shifts in the spectrum of the companion of Sirius. According to the theory of relativity the frequency of the radiation at the Sun's surface is less than that on Earth;* the lines in the solar spectrum will therefore be shifted toward the red, as compared with lines produced in the laboratory. The shifting is due to the Sun's gravitational field. Of course, similar shifts occur in the spectra of other stars; the Einstein effect being directly proportional to the mass of the star and inversely proportional to its radius. Now in the case of the companion of Sirius, which has a radius of one-fiftieth that of the Sun but is approximately of the same mass, the gravitational force on the surface is very great – around 2500 times as much as on the surface of the Sun – so that the Einstein shift of the lines is considerable. For the Sun, however, the shift at wavelength 4000 A amounts to only 0·008 A and, moreover, complications are introduced by other effects which are as yet imperfectly understood. We may be sure that the Einstein effect exists, but in the case of the Sun it has not yet been definitely measured.

Neither is it an easy matter to measure the deflection of light rays in the Sun's gravitational field, although here too there is no doubt of the reality of the phenomenon. Relativity theory predicts that light rays should be 'bent' when passing

* Being $\nu(S)$ and $\nu(T)$ the frequencies of a certain radiation respectively on the Sun and on the Earth, we can write:

$$\nu(S) = \nu(T) + \Delta\nu$$

the difference of the two frequencies being very small. The gravitational potential at the surface of the Sun is equal to fM/r, where f is the coefficient of attraction, M the mass of the Sun and r its radius. As the gravitational potential at the surface of the Earth is very small, compared with that of the Sun, we can write:

$$\Delta\nu/\nu(T) = f-M/rc^2,$$

where c is the velocity of light. $\Delta\nu$ is therefore negative, that is the frequency of the radiation at the Sun's surface is less than that on the Earth.

through a strong gravitational field such as that of the Sun. During the course of a year, the light from various stars reaches us by passing close to the Sun, but at such times the stars cannot normally be studied – they are of course close to the Sun in the sky, but the bright background of the sky itself obscures them. Total eclipses, however, provide real opportunities. For a brief period, during totality, the brilliant photosphere is hidden, and nearby stars become visible against a comparatively dark background. At such times, very precise positional measures are possible.

Observations of this kind, first made during the total eclipse of 29th March 1919, are carried out as follows. Photographs of the Sun are taken, together with stars nearby (say within a field of 4 or 5 degrees); using a long-focus lens with a wide field. Two or three months later, when the Sun has moved some way along the ecliptic, photographs of the same star-field are made, using exactly the same equipment and covering exactly the same area of the sky. From a comparison of the two star-fields – one containing the eclipse of the Sun, the other without the Sun at all – the differences in the co-ordinates of the stars are obtained, and the 'bending' of the light-rays from them due to the presence of the Sun may be calculated.

The deflection of rays of light from a star close to the limb of the Sun is, according to relativity theory:

$$\Delta = \frac{4fM}{rc^2}$$

From this formula, Δ is calculated as $1''{\cdot}75$, so that this is the apparent angular shift in position of a star which appears to lie close to the limb of the Sun. It will be recalled, from the original corpuscular theory of light of Newton, that the corpuscles were supposed to be influenced by the Sun's gravitation, but on Newton's theory this deflection is less, being exactly equal to half that predicted by relativity, i.e. $0''{\cdot}87$.

For the 1919 eclipse, two expeditions to the zone of totality were organized by Greenwich Observatory. One was dispatched to Prince Island, in the Gulf of Guinea, and the other (in which Eddington took part) to the island of Sobral off the Brazilian coast. At this time the Sun was near the Hyades star-cluster, so that it lay in a region rich with stars of the 5th and 6th magnitudes. In mid-July, when the Hyades could be studied at night, comparison photographs were taken. Though the expeditions did not enjoy good meteorological conditions, the average value obtained gave $\Delta = 1''\cdot79$, not very different from the value predicted by Einstein. Since 1919 further eclipse studies have been made, using more precise methods and better equipment. The mean of determinations made during the eclipses of 1919, 1922, 1929, 1936, 1947 and 1952 results in a value of $1''\cdot97 \pm 0''\cdot20$.

While there is no doubt that these results confirm the theory of relativity, it must be stressed that the degree of uncertainty in the figures is still considerable. The main trouble lies in the difficulty of measuring the small angles involved, especially when the stars concerned are some distance from the Sun's limb. Moreover, the laws governing the decrease in 'light-bending' with increasing distance from the solar limb are not yet understood, although they must involve certain errors in the derived results. It is, however, safe to assume that future determinations will be made with greater accuracy, and it is probable that the real value for the deflection is slightly higher than the present average result.

The Chromosphere

During the eclipse of 1870, Young made the first observations of the so-called flash spectrum, and so established the existence of the *chromosphere*, so named because of its intense red colour. The flash spectrum is visible for a few seconds between second and third contacts of the solar and lunar disks. The different layers of the photosphere may be distinguished by their optical depth, and the values converted into kilometres by theoretical calculations, assuming the gas to be in equilibrium. Zero height of the photosphere is defined as the visible limb of the Sun. The flash spectrum is seen when the continuous spectrum disappears, and the Fraunhofer lines appear not in absorption, but in emission. By observing with a prism placed before the telescope lens or mirror, since at the moments of second and third contact a kind of 'slit' is formed between the disks of the Sun and Moon, the emission lines are seen as bright crescents of different amplitudes; the amplitudes vary according to the height above the photosphere of the elements producing the lines. From the duration of visibility of the emission lines, which ranges between 2 sec for the shortest arcs and around 40 sec for the largest, it is calculated that the layers of the chromosphere extend from 500 to 14,000 km above the photosphere.

A picture of the chromosphere may be obtained in various ways: by photographing the Sun directly, during an eclipse, either in white light or with coloured filters, when what looks like a rough sea made up of 'flames' shows up around the rough, mountainous limb of the Moon, or by spectroscopic examination, using tangential or radial slits.

If, in the first case (tangential slit), the Hα line is examined, it is seen that there is a double reversal; in the middle dark absorption and emission occurs to both sides, so forming a thin spindle shape, where the extension of the tangent to the disk reaches into the higher levels of the chromosphere. In the second case (radial slit), the Hα line appears in emission, looking like an arrow not far from the limb. With monochromatic filters, the clearly-defined edge of the photosphere may be seen in Hα, even in full sunlight, surmounted by a thin, less luminous and undulating layer. This was described by Secchi, in his visual observations, as a 'burning field' with small

flames rising from it. W. O. Roberts termed the highest flames 'spicules'. The average height of clearly-visible spicules above the photosphere seems to be about 10″, and the width of each spicule 1″ to 2″. Above the photosphere, the undulating surface of the chromosphere extends to about 6″; with the spectroscope slit aligned radially to the limb, the $H\alpha$ line rises up to 10″ or 11″, and observations made at Arcetri show that it extends 2″ further at the poles than at the equator during periods near solar minimum. At solar maximum, the heights are however equal. An individual spicule reaches its greatest altitude in about two minutes, and then disappears. As Secchi noted, the 'flames' nearest to sunspots converge on the zones of greater disturbance as flares, whereas near the pole they are straight, thin and very luminous. In any case, spicules are phenomena occurring in the comparatively undisturbed regions of the Sun, while the situation in active areas is much more complex – due partly, no doubt, to the presence there of strong magnetic fields. The density of the photosphere is estimated as 10^{-8} g/cm³, while that of the chromosphere is 1000 to 10,000 times less.

The flash spectrum is really the emission spectrum from the different layers of the chromosphere. During solar eclipses, great attention has been paid to it – especially by S. A. Mitchell, who has discovered and identified 3500 emission lines in the region between 3060 and 8860 Å. It might be thought that the flash spectrum must be the same as that of the photosphere, with emission instead of absorption lines, but in point of fact it is not an exact reversal; there are several winged lines due to metals, and also neutral atoms, such as those of He and O, in highly excited states. It is also noticeable that the degree of excitation differs from one eclipse to another, according to whether the Sun is near maximum or minimum activity.

The emission lines which reach to the highest levels of the

chromosphere are the H and K lines of Ca^{II}, which attain roughly 14,000 km, followed by the $H\alpha$ line at 12,000 km, the D_3 at 7500, and ionized metals such as Fe^{II}, Ti^{II} and Ca^{II} at 2500 km. Many of the lines making up the flash spectrum reach to approximately 1000 km, while at a lower level, 500 to 300 km, are neutral atoms; bands of CN are also present. From this point, the continuous spectrum is visible to the limit of the Balmer series.

The strongest lines of the chromosphere show the phenomenon of absorption or double reversal, which may also be seen in the laboratory when with a source such as an electric arc, which produces emission lines, layers of cooler vapour surround the hotter layers; an absorption line is visible in the middle of the emission line. Typical examples of this are shown by the intense H and K lines of Ca^{II}, and the $H\alpha$ line. At times when the Sun is not eclipsed, it is possible to use the large solar towers to obtain photographs of parts of the chromosphere spectrum, under high dispersion, so that the double reversal can be seen in many lines. The phenomenon may be explained in terms of the different levels reached by different elements of various densities.

It is known that elastic collisions between electrons, ions and complete atoms take place in gases, and that these follow well-known laws for different types of particle. Hence it is important to consider the kinetic temperatures at various levels in the Sun. Unfortunately the results of various experimental and theoretical investigations are not in good accord. Taking into account the height reached by the chromosphere, as well as the presence of helium emission lines and the width of the H and He lines, it seems that the temperature of the chromosphere must be much greater than that of the photosphere. Yet when we consider the wings of the metallic lines, the excitation of metallic atoms, the distribution of intensity in the Balmer continuum, and the lack of helium absorption

lines at 500 km, it seems that the temperature should be relatively low. The latest information indicates that the temperature of the chromosphere is less than 10,000°. The relative abundance of metals is the same as with the photosphere, and there is no reason to suppose that this abundance varies with height. To determine the amounts of hydrogen and helium in the chromosphere is more difficult, since this depends to a great extent on the temperature and on other conditions which establish the ionization equilibrium.

It may be concluded that below 4000 km, the chromosphere is a gas at a relatively low temperature; the greater part of the hydrogen is neutral, wings being produced by collisions or radiation in agreement with Saha's equation. Above 6000 km there is a layer of hotter gas consisting mainly of ionized hydrogen. The free electrons transmit the flow of heat toward the base of the corona, so creating a marked temperature gradient in the lower layers. The density gradient is however small, and the pressure gradient about zero. In fact, the transition layer from high to low levels in the solar atmosphere is the site of three important physical changes: the temperature gradient is at its largest, neutral hydrogen becomes ionized, and the optical depth of radiation from the ultra-violet (Lyman) continuum is small. In any case, it may now be said that the problem of the heating and sustaining the chromosphere has been solved. It has been suggested that the granulation present in the middle layers of the photosphere gives rise, by some means or other, to jets or flowing of material in the lowest and highest layers of the chromosphere, and that when these are halted at the base of the corona their kinetic energy is transformed into heat affecting the surrounding gas. It is possible that theory and observation will provide an answer to the origin of the spicules; this may involve the motion of granules in the photosphere, and the dissipation of energy in the upper chromosphere and in the corona.

In the following pages, attention will be paid to the phenomena occurring in the chromosphere, and how these phenomena are being studied in monochromatic radiation from gases such as hydrogen and calcium vapour.

The Corona

Beyond the well-defined limb of the Sun, the light falls off very rapidly, so that in broad daylight the corona cannot be seen. Denoting the distance from the centre by r, and the distance out from the limb – in minutes of arc – by h, Waldmeier defined three regions in the corona. The innermost of these lies between $1'{\cdot}0 < r < 1'{\cdot}2$; $0' < h < 3'$, the middle corona between $1'{\cdot}2 < r < 1'{\cdot}8$, $3' < h < 13'$, and the outer corona $r > 1'{\cdot}8$, $h > 13'$. The inner corona may be studied with coronagraphs which have been set up at various observatories, but the outer corona, with a brightness 10^6 times less than that of the Sun itself, is observable only during total eclipses. Almost all the radiation from the inner corona is in the continuous band, since it is light diffused from the photosphere; only 1 per cent of light from the inner corona is due to its own luminosity and so shows emission lines.

The corona appears as a 'pearly' halo around the Sun's disk, with streamers reaching out to a distance of several radii. There are also various coronal arches and brighter rays. The arches are seen above disturbances on the solar photosphere – the filaments and prominences (to be discussed below). The arches often are multifarious, of concentric shape, alternatively dark or bright, and appear to pulsate with a velocity varying from 0·5 to 3 km/sec. A possible explanation of this effect is that the electron density inside the arches is much less than in the adjacent regions.

Streamers appear in the region of the equator and in middle and higher latitudes, with rays extending around the poles. The complete picture of the corona suggests a pattern of lines

of force around a magnetic sphere. The general form of the corona changes from eclipse to eclipse. Near maximum activity it is circular, but has a sort of 'butterfly' appearance, with streamers more or less evenly distributed. At times of

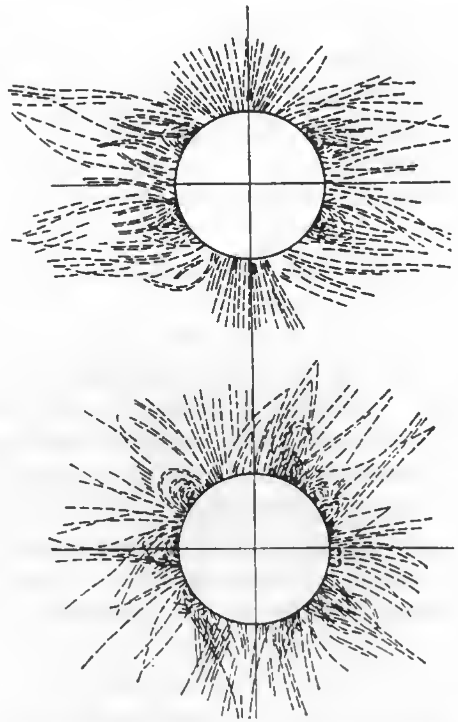


FIG. 13. Equatorial corona at minimum solar activity (*above*). Polar corona at maximum solar activity (*below*).

minimum activity, the corona is elongated in the region of the equator – due to the effect of conspicuous rays extending around the poles. Three different types of corona may therefore be distinguished – 'polar', 'intermediate' and 'equatorial'. The types are related to the eleven-year solar cycle; maximum

activity corresponds to the equatorial type, appearing one or two years before the actual maximum, and minimum activity with the polar type, visible for the same order of period before actual minimum. It may therefore be inferred that near solar maximum, the shape of the corona is largely influenced by disturbances taking place in high latitudes.

Cine techniques introduced by Lyot, using the coronagraph, have provided a great deal of information about the movement of the inner corona, and have shown that brightness changes occur over relatively short intervals. Some areas become very brilliant over a brief period, while other parts of the corona change too slowly for the sequences to be definitely followed. Stereoscopic examination of slight changes of motion may be carried out by combining photographs taken at a suitable interval, but the differences observed are not significant. Such motion as may be measured is rather less than 1 km/sec, and this could be purely the effect of solar rotation.

Despite these inconclusive results, which show the absence of rapid movement within the corona, it is probable that the motions are very complex, and due to vortices which are difficult to resolve from photographs taken consecutively. However, it may be shown that when the prominences are in rapid motion, the matter of the corona proper is relatively tranquil. Streamers, jets or clouds appear here and there in a manner reminiscent of the Earth's polar aurorae, but exhibit little actual movement. Cinematography makes it evident that clouds and arches appearing at various distances from the solar globe are difficult to study from the point of view of individual movements, but that changes observed in the corona are most likely due to variations in the intensity of different areas. Streamers and clouds in the corona assume complex forms, and move along definite trajectories, the origin of which is so far unknown.

Photometers, spectrophotometers and the Lyot coronagraph are extensively used during total eclipses, while photographic, bolometric and photoelectric methods serve also to study the total luminosity emitted by the corona. Because of diffusion in our own atmosphere – which has a particularly severe effect upon that part of the corona covered by the Moon during an eclipse – and also the inevitable instrumental errors, the various determinations are by no means in perfect accord. At this point, it should be noted that the total light received from the corona is only half that of the full moon, and is therefore equivalent to 1×10^{-6} times the brightness of the Sun (though at solar maxima the intensity may be rather greater). The falling-off of intensity of the corona in a radial direction outward from the limb has been measured during several eclipses. Neglecting the variation of brightness with the state of the solar cycle, and also neglecting brightness variations due to differences of heliographic latitude, Baumbach has tabulated the following results; where *r* denotes the distance from the centre of the Sun, in solar radii; *h*, the distance from the limb in minutes of arc; and J, the brightness, expressed in millionths of the intensity of the centre of the Sun's disk:

r	*h*	J(*r*)
1·0	0·0	4·04
1·2	3·2	$5{\cdot}47 \times 10^{-1}$
1·6	9·6	$7{\cdot}04 \times 10^{-2}$
2·4	22·4	$9{\cdot}06 \times 10^{-3}$
3·5	40·0	$2{\cdot}57 \times 10^{-3}$
10·0	144·0	$1{\cdot}68 \times 10^{-4}$

In 1860, Secchi had shown that the light from the corona is partially plane polarized; since then, much more detailed work has been carried out, using the polariscope together with a camera fitted with a short-focus lens of small aperture,

and an analysing system of Nicol or Wollaston prisms.* Although the measures are not yet in close agreement, it seems definite that polarization increases up to $10' \sim 12'$ from the Sun's limb, after which a decrease is noticeable.

The fact that light from the corona is partially polarized shows that it is not due entirely to thermal emission, as used to be thought, but may instead be due to sunlight diffused by free electrons. From this hypothesis, Baumbach has revised the theory, and has calculated the degree of polarization (P) as a function of the distance from the Sun's limb. Agreement is not very satisfactory, but it may now be assumed that the theory is supported by observational evidence. This confirms the view that the phenomenon may be explained, qualitatively, by regarding the light of the corona as a blend of the partially polarized component (due to diffusion by free electrons) and the non-polarized component (due to the surrounding Zodiacal Light). A further fact has also been established: the degree of polarization at the pole is much less than at the equator, since the corona at the pole is not so brilliant as at the equator.

In 1868, Rayet noticed that the inner corona yielded a continuous spectrum; in the outer corona, absorption lines were observed by Janssen in 1871. The change from inner to outer corona is found to take place at about 10′ from the limb. Fraunhofer lines appear about 4′ from the limb, and increase with distance, while emission lines are visible through a distance of 6′ to 7′ from the limb.

Lockyer was the first to measure the wavelengths of emission lines in the corona. Originally he studied six such lines,

* The degree of polarization is conveniently expressed by the formula:

$$P = \frac{I_e - I_r}{I_e + I_r}$$

where I_e represents the intensity of the tangential electric component and I_r that of the radial component.

and found that the green line is the most intense. Subsequently Lyot measured some 30 lines, both during eclipses and in daylight. For a long time the elements responsible for the lines could not be identified, and the green line was attributed to an unknown gas which was given the name 'coronium'. A classification of the lines was drawn up by using spectrograms of the coronal rings, obtained during eclipses by means of a prism objective. Near prominences, and disturbed areas in general, these rings appeared with condensations of different shapes, but showed similar structure, thereby suggesting that they are due to the same substances – or at least to the existence of a similar state of excitation or ionization.

Several classifications were proposed, and Lyot's, which appeared to be the most convenient, was adopted, following the discovery of 'forbidden' lines of Fe^{VII} in some variable stars and novae – since these lines were also thought to exist in the corona. In point of fact, forbidden lines are produced by gases at densities appreciably lower than have been obtained in the laboratory – hence the term 'forbidden' – and in space these conditions are naturally ideal for long mean free paths which electrons need to produce these lines.

Research of this kind enabled the Swedish physicist Edlén to demonstrate experimentally and theoretically that strongly-ionized atoms of iron, nickel and calcium are responsible for most of the emission lines in the corona. Iron with 9, 10, 12 or 13 electrons, less than the 26 of its neutral state, produces intense lines in the corona. These may be tabulated as at the top of the next page, in decreasing order of intensity, denoting the 5303 A green line as 100 units.

The wavelength is shown against estimated intensity, according to Edlén's identifications. The ionization potential (the energy required to remove the last electron, so forming an ion) and the excitation potential (the energy of the transi-

Class	*λ in A*	*Intensity*	*Identification*	*Ionization potential*	*Excitation potential*
II	5302·9	100	Fe^{XIV}	355	2·34
II	3387·8	16	Fe^{XIII}	325	5·96
II	10746·8	55	Fe^{XIII}	325	1·15
II	10797·9	35	Fe^{XIII}	325	2·30
I	7891·9	13	Fe^{XI}	261	1·57
I	6374·5	12 approx.	Fe^{X}	233	1·94
II	6701·8	4 approx.	Ni^{XV}	422	1·85

tion level higher than the fundamental level of the ion) are expressed in electron volts. The classification is derived from observations of lines showing similar variations of intensity during eclipses, and similar intensity-distribution around the disk. The green line at 5303 A and the red line at 6385 A have been discovered in the variable star RS Ophiuchi. The lines in the infra-red have been discovered by Lyot in full sunlight.

The more intense emission lines show considerable equivalent width : 0·8 A for the line 5303 A, 1·0 for the line 6374 A, and 1·1 for the line 6702 A. This effect is a result of the kinematic condition within the corona. Because of the extreme rarefaction of the material in the corona, the widening of the lines can be due only to a Doppler effect, and this has been confirmed by Lyot, who has found that in each case the width is proportional to the wavelength. For the 5303 A line, a mean velocity of 25 km/sec has been obtained; correspondingly the temperature of the corona should be $2{\cdot}1 \times 10^6$ degrees. Coronal lines to the contrary of those of prominences, show no macroscopic Doppler effect, only zones of disturbance show occasional changes of velocity ranging between 5 and 20 km/sec. Lyot has further investigated the rotation of the corona, which rotates as the sunspots and prominences, having a greater velocity at higher latitudes.

The great significance of the corona in the general picture of solar phenomena has led suitably-equipped observatories at high altitude to undertake continuous studies of the intensity

changes in the emission lines, particularly those at 5303 A and 6374 A. At the Federal Observatory at Zürich, daily measurements of intensities are carried out, taken at a fixed distance ($\sim$1′) from the solar limb, and at every 5° on an

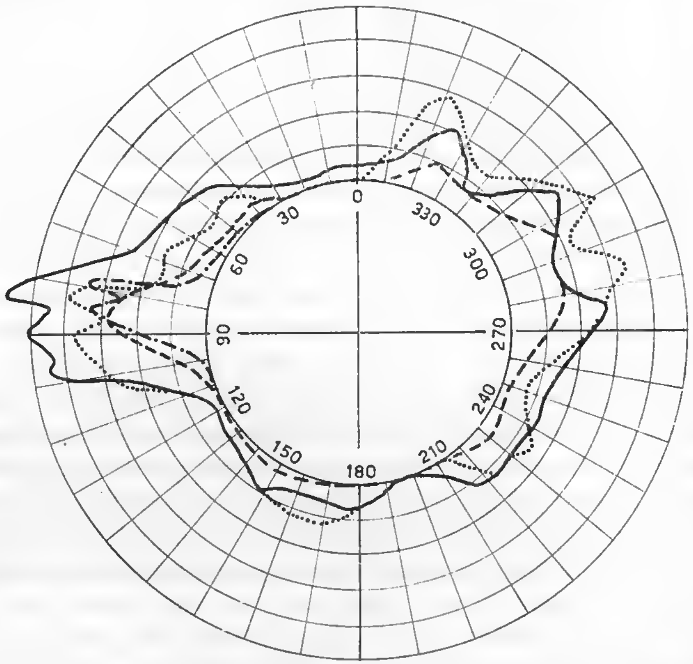


FIG. 14. Intensity of the coronal line 5303 A, measured at the Pic du Midi (1), Arosa (2), Wendelstein (3), and Zugspitz (4). (Kiepenheuer.) (1 —— 2 · · · · · · 3 – – – – 4 – . – . – .)

empirical scale or by means of photometry. The results are published in the *Quarterly Bulletin on Solar Activity*. It is thus possible to build up a complete daily profile of coronal activity all around the circumference of the Sun. To this work must be added studies of the coronal streamers which are available at times of non-eclipse. The information is most helpful in

correlating the relation between streamers and prominences throughout the course of the eleven-year cycle – particularly in view of the fact that this particular relationship is not yet at all well understood.

The existence of very strongly ionized atoms in the corona leads to the conclusion that the kinetic temperature must be extremely high – of the order of a million degrees. Gases at such temperatures are very rarefied, although the density at the lower boundary of the corona must be around 10^{-11} times that of the Earth's atmosphere. Yet despite the high temperature, the energy emitted by the corona is slight when compared with the radiation from the Sun itself. The corona consists of virtually isothermal gas, in which most of the atoms are in a state of highest ionization, and are moving at great velocities – the protons at about 200 km/sec, the electrons at 8000 km/sec. Indeed, the collisions are so violent that many electrons are thrown out from the nuclei of the atoms. The distribution of matter in the corona presents continuously changing structural details, but without much noticeable interchange of large masses. The gas is rendered visible by the diffused light from free electrons, and by the spectral lines emitted by ions, upon which is superimposed the Zodiacal and diffused light from the sky. The diffused light of the electrons accounts for 99 per cent of the total light; it is of the same colour as light from the Sun itself, and is partially polarized.

Solar Activity

As we have seen, monochromatic images of the Fraunhofer lines in the solar spectrum may be obtained by means of the spectroheliograph or with Lyot filter. Though various particular lines are of general importance in investigations of the distribution of different gases, the most important of all are the H and K lines of calcium and the Hα line of hydrogen.

When the wings of the K line (known as K_1) are examined, the brightness of the Sun's image is found to be as intense as that one in white light, even with granulation and the presence of faculae. Shifting the investigation toward the centre of the line, where inversion takes place (K_2) it may be seen that the faculae are larger and brighter, and the granulation more clearly marked and of greater contrast, than when viewed in white light. If now we study the centre of the line (K_3), we find that the faculae extend even further, and cover all the sunspots, which then are no longer plainly visible. These faculae have been termed 'bright flocculi' by Hale, and are evidently at a much higher level than the similar features noted at the wings. They may be due to areas of excited calcium in the chromosphere, where the temperature is higher than in the photosphere. Such faculae nearly always precede or follow the events of the groups of sunspots, but may also appear in zones free from spots – in which case they are neither so brilliant nor so extensive, probably covering spots which are too small to be seen as such.

Photographs taken in the light of the H and K calcium lines show marked differences from those taken in Hα light. This is also the case with the components Hα_1, Hα_2 and Hα_3; these differences are increasing from the first to the third comparatively to the photographs taken in white light or in the continuous spectrum. As one moves toward the centre of the line, to higher levels of hydrogen, the granulation assumes a more typical appearance – very different from the appearance in calcium light, and arranged in small branches, or leaves, fairly evenly distributed around the quiet areas, though in disturbed regions near spots the appearance is vortex-like, resembling a cyclone. In these disturbed regions, too, brilliant flocculi or faculae may be seen, similar in form to those in calcium light, though generally less bright and extensive. In both calcium and hydrogen photographs there may be dark areas in shape

of 'filaments', which stretch along in the direction of the solar parallels or meridians; they are often associated with disturbed areas, though they may also appear scattered here and there at all latitudes. These filaments must be clouds of absorbing hydrogen, cooler than the underlying gases but at a higher level, so projecting into the chromosphere and sometimes shooting outwards to a tremendous distance above the surface of the Sun, and appearing as prominences. In the light of Hα wavelength these features, which may be called 'filament prominences', appear dark by contrast with the calcium light from the chromosphere.

Recently, successful photographs have been taken of the Lα line at 1216 A, in the far ultra-violet (Lyman series). As rocket photographs have already shown, the Sun's emission at this wavelength is very strong, so that monochromatic records of this particular line are of considerable interest. On 13th March 1959, the United States Naval Research Laboratory launched an Aerobee rocket from the proving ground at White Sands, New Mexico. It carried a spectrograph fitted with two high-resolution gratings. The first of these served to isolate the Lα line in the solar spectrum; the second converged the monochromatic beam from the first grating, and focused an image of the Sun, in Lα light, on to the photographic plate. In order to eliminate the astigmatism on the image of the first order of 3·6 mm, the first grating is ruled on a concave ellipsoidal surface, and the second on a spherical surface. The photographs were taken from a height of 200 km, using exposures of from 1/200 to 7 seconds. They showed bright patches, or faculae, which coincided in position with the brilliant calcium flocculi, but were more extensive, emphasizing the intensity and amount of ultra-violet radiation from these disturbed regions in contrast with the surrounding darker areas. The dark filaments in Hα and Ca^{II}, as in Lα, showed up as large dark regions. From these

preliminary results alone it may be assumed that a great deal of fresh information will be gained from studies of the Sun's ultra-violet spectrum; this in turn is of considerable importance in studies of solar effects upon terrestrial phenomena.

Another phenomenon often associated with faculae, though sometimes occurring independently, is that of the solar *flare*. It must however be added that flares occur in or around disturbed areas between sunspots, or in contact with spot-umbrae. Flares usually form very rapidly, but last for only a few minutes, making their appearance as isolated points or very bright groups in regions extended to as much as 5000 millionths of the solar hemisphere. As sunspots are associated with powerful magnetic fields, they must also give rise to electric currents. It can be assumed that flares are electrical in origin, and are not unlike similar phenomena which occur in our own atmosphere, though they are of course on an immensely larger scale.

By taking a series of exposures with a spectroheliograph or with a Lyot filter, the formation and development of a flare can be followed throughout the few minutes of its existence. Flares are by no means uncommon, specially around the maximum of solar activity; with a large group of sunspots, many flares may be seen during the course of a day, some of them covering large areas, while others are minute. About 100 of these small flares, each lasting no more than a minute or so, may occur during any given day of high solar activity. So far, the origin and significance of the flares is not understood. All we can say for certain is that flares are of great significance in solar physics and have marked effects upon terrestrial phenomena.

Studies of the brilliancy of flares leads to an estimate of their average density; the value seems to be of the order of $1 \sim 3 \times 10^{12}$ electrons/cm^3, or 3×10^{-12} g/cm^3. Sometimes very brilliant flares are visible in full sunlight; the first record

of such a flare was obtained by R. Carrington and R. Hodgson on 1st September 1859. During the last cycle, which began in 1954, similar observations were made.

A typical case of a 'white' flare was that described in detail by Waldmeier on 23rd March 1958. It was first noticed at $10^h\,5^m$, near a sunspot on the solar limb; it could be photographed without difficulty. It displayed a number of bright points, each about 5000 km in diameter, joined up by luminous filaments. Assuming a value of 0·42 for the brightness of the undisturbed surrounding area of the photosphere, on a scale in which the centre of the Sun's disk is taken as unity, the flare itself had a brightness of 0·72 – that is more than the 70 per cent. Examination in Hα light, using a Lyot filter, revealed the presence of bright flocculi. Photographs in Hα light showed the flare in all its brightness, rising on the chromosphere near the edge of a sunspot, and spouting hydrogen jets to a height of 35,000 to 60,000 km. As the flare developed, it therefore gave rise to a typical eruptive prominence, the two ends being connected by visible links. Since the flare occurred near the limb, it provided an excellent opportunity for investigating its relationship with the corona; no increase in intensity in the emission lines of the corona, nor any Doppler effect, could be found. Only when the flare was all but spent was a strong condensation in the coronal material noticed, together with an increase in the intensity of the emission lines. Similarly, photometric measurements of the corona showed isophotes which are perturbed corresponding with the position of the prominence. This particular flare developed just outside the penumbra of the sunspot, which is by no means unusual; it is in fact a favoured position for flares associated with spots. It seems that the mass of gas rising from the photosphere around the edges of a spot sets off the process in the chromosphere and the innermost part of the corona.

Observations of the areas in which flares appear, when near

the limb, show that we are dealing with three-dimensional objects, rising only to the level of the middle chromosphere. One characteristic of flares is that they may at times be completely detached from the photosphere, or else joined to it only by luminous fringes. A flare originates in the chromosphere, but probably it develops in the region of the corona. Little internal motion takes place in the flare – usually only a slow ascending movement in the first stage of development of an intense flare. The velocity is about 10 km/sec.

The number of flares which can be seen in a disturbed region of the Sun is proportional to the Wolf number, so that if R = 150, then one may assume a daily average of 10 flares, of which at least two will be of what is called 'importance two' on a scale of three. The most clearly visible flares occur in sunspot groups C, D and E, and a few in F (see fig. 3). Mention should also be made of the so-called 'micro-flares', first observed by Lyot through the clear atmosphere of the Pic du Midi. These small features are about 1″ in diameter, and last from 5 minutes to 15 or more, with a brightness similar to that of the common flares. Brilliancy curves have been determined by various observers, and are asymmetric, with a rapid rise of not more than 5 or 10 minutes followed by a slower descent.

The spectra of a flare show up the centre of the absorption Fraunhofer lines, in emission, the most intense appearing in the Balmer series, the helium line 10832 A and the lines of Ca^{II}. More than a hundred emission lines have been found between 5000 A and 6000 A in a very bright flare, including a large number due to neutral or ionized metals. Bright flares also give a continuous spectrum which is, however, difficult to see. Sometimes, too, there are phenomena in the Hα line which Ellerman has called 'bombs'. Around this line, and extending about 30 A, the continuous spectrum becomes very bright, while the Hα and other Fraunhofer lines appear normal. This

suggests an explosion of radiation originating deep in the photosphere (plate VII). During this process, the absorption line is generally shifted toward the violet, due to the presence of gases rising with a velocity of the order of 5 km/sec. Instead, the bright emissions may reach a velocity of up to 1000 km/sec, and the increase in energy is comparable with that produced in a thermonuclear reactor. Flares may be regarded as typical phenomena of the chromosphere, but the bombs or 'moustaches' (so called because of their appearance) originate in the photosphere or sub-photosphere. They may be connected with the first stage of flare development.

In 1956 a rocket, equipped with radiation detectors, was launched at the time of occurrence of a flare. Besides the line Lyα, the detectors recorded intense radiation due to X-rays in the region below 8 A.

For convenience, flares have been classified according to the table given below. On the scale adopted, 1 denotes the

Importance	*Average Duration*	*Range*	*Limits of Area*	*Average Width, Hα*
1	20^m	4^m–40^m	100–250	2–8
2	30	10–90	250–600	2·5–10
3	60	20–150	600–1200	10–20
3+	180	1^h–7^h	>1200	—

least intensity, 2 intermediate, 3 major intensity, and 3+ exceptional intensity. This scale has been derived empirically, although a more precise system could be used based on photoelectric measurements of intensity and plotted areas. The 'importance' of the flare is based on the following data: the duration of the flare from beginning to end, area of the region or regions of Hα emission, effective width of the Hα line in Angströms at the most intense parts, and the central Hα intensity expressed as a fraction of the continuous spectrum outside the line or in terms of the intensity of the depth of the Hα absorption line.

The areas given above are measured at the time of the maximum development of the flare, and are given in units of 10^{-6} times that of the visible hemisphere; they have been corrected for perspective effects by multiplying the area observed by sec θ, where θ is the heliocentric angle. The Hα widths are expressed in Angströms. There is no doubt that the average width of the line increases as the flare develops –

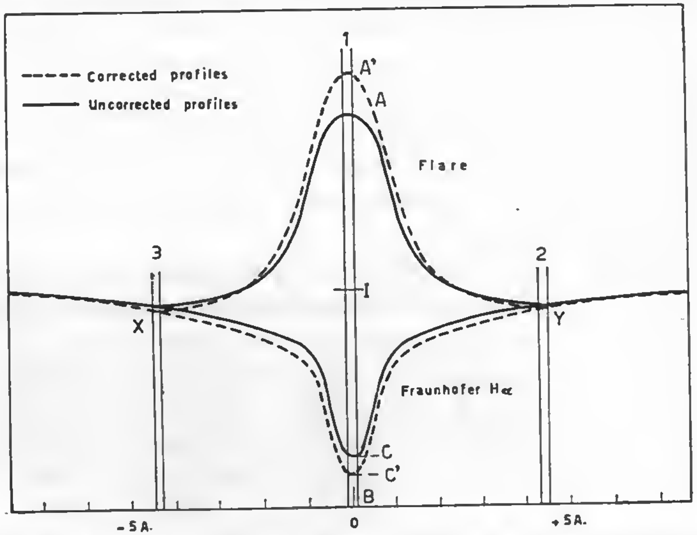


FIG. 15. Profile of the Hα line, normal and with flare (M. A. Ellison).

naturally taking into account the fact that measurements are influenced because the line-width is a function of the heliocentric angle. The profile of the Hα line is shown in fig. 15. XY is the effective width of the line in Angströms; AB/BI is the intensity at the centre, expressed as a fraction of the continuous spectrum; AB/BC is the intensity at the centre in terms of the chromospheric background. The observed profiles represented in the figure with full line must be corrected for instrumental errors; the corrected profile is represented

by the dotted line. Measurements made at various observatories show that for flares of importance 1, the intensity at the centre of the Hα line covers at least 80 per cent of the

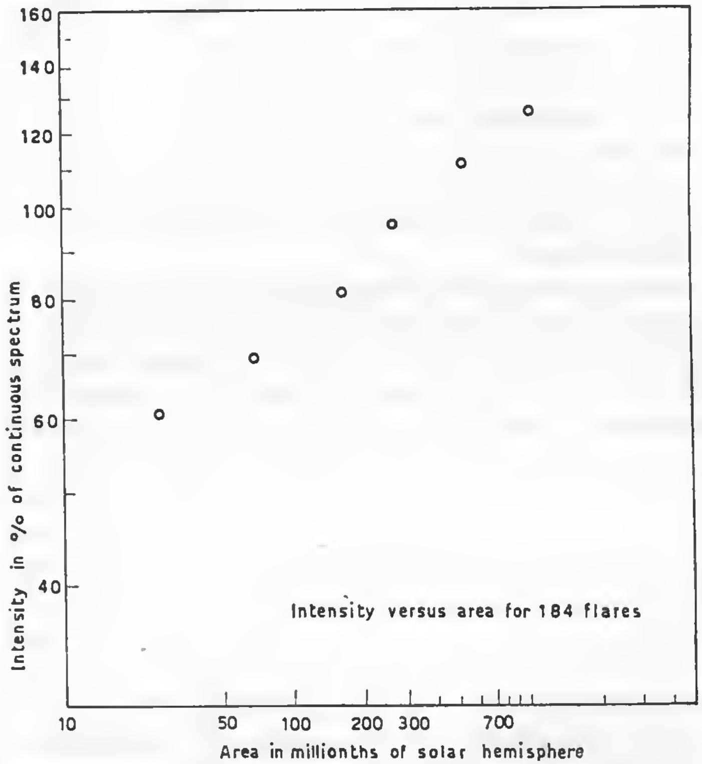


FIG. 16. Relationship between area and intensity of flares (M. A. Ellison).

continuous spectrum; for importance 2 flares, 90 per cent; and for importance 3, 130 per cent. Fig. 16 shows a comparison between the flare-areas and their intensities expressed as a percentage of the continuous spectrum.

Flares are obviously of the greatest significance in solar

research. Probably they are the sources of the ultra-violet radiation, eruptive prominences, particles which produce polar aurorae, cosmic rays and radio waves. It is therefore easy to see why so much time has been spent in keeping a continuous watch on the Sun. The Bulletin compiled at Zürich every three months, lists the results of flare reports from some 30 stations all over the world. From each station comes information regarding the beginnings and ends of flares (given in U.T.), the heliographic co-ordinates, the maximum Hα widths, the areas (in heliographic degrees), and the maximum intensities as a percentage of the continuous spectrum.

During total eclipses, 'flames' have often been seen round the Sun's limb. Lockyer and Janssen in 1868 were the first to observe them with the spectroscope in full sunlight. Sighting the slit of the spectroscope at the edge of the Sun in the place where a prominence existed, an intense emission spectrum was seen. From that year continuous observations were made; the slit was widened in order to see their shape. Therefore a number of monochromatic images appeared, corresponding to their emission lines. It was thus possible to study various characteristics of the flares – shape, variation, velocity and position – throughout the whole of the 11-year cycles.

After the invention of the spectroheliograph, it was found that besides the bright flocculi or faculae seen as monochromatic images, there also appeared dark flocculi or 'filaments' in the light of the Ca^{II} and Hα lines. The name filament is derived from the appearance of these features. It was also noticed that the filaments rotate according to the Sun's rotation, travelling from the eastern limb toward the central meridian, and disappearing at the western limb, while the shape changed because of perspective effects. If at the central meridian the form was that of a long, dark filament, it became wider as it neared the limb, until it stretched out from

the limb into the sky showing that it was a prominence. The filaments are therefore prominences, and the fact that a 'filament-prominence' appears at different positions of angular perspective enables their shapes, dimensions and evolution to be studied.

In his celebrated visual observations of prominences, Secchi had introduced the terms 'quiescent' and 'eruptive'. Quiescent prominences are relatively stable, lasting for more than one solar rotation, and developing slowly; eruptive prominences evolve and vanish very quickly. Since then, various more complicated classifications have been proposed by various observers, based on shape, evolution, or position on the Sun. The positions are characteristic; they differ from those of sunspots, but they too are affected by the 11-year cycle. Prominences tend to appear more frequently in two zones, one at low latitudes and the other at higher latitudes. In the first zone, eruptive prominences may be observed, originating and developing in the neighbourhood of sunspots; quiescent prominences are usually formed in latitudes 5° or 10° higher. In the second zone are the high-latitude 'polar prominences'. They first appear three years after sunspot maximum, increasing in activity during the following years and migrating toward the poles until the arrival of the next maximum, after which they disappear.

The spectrum of a prominence is very similar to the flash spectrum. Usually, the emission lines of hydrogen, helium (D_3) and Ca^{II} are visible, but when the prominence is more intense and eruptive lines produced by neutral or ionized metallic atoms are present. Differences between the spectra of various prominences seem to be due to changes in intensity rather than to different conditions of excitation. Such conditions arise because the prominences are at temperatures of the order of 10^4 degrees K, and rise up through the Sun's atmosphere where the kinetic temperature is about a hundred

times higher, due to the emission of ultra-violet radiation and the presence of X-rays. The highest and outermost parts are therefore subjected to very intense radiation from the corona, which however does not reach the lower and innermost parts of the prominence.

At the edge of the Sun, prominences appear luminous, and assume various forms – trees, mountains, columns and fountains with multiple arches. When projected against the disk, however, they appear in the shape characteristic of the filaments, i.e. more or less curved. These latter are quiescent prominences which appear dark against the disk because the rarefied gases at high level absorb the light radiated from the photosphere. These filament-prominences are thus elongated, flat and thin, like flexible blades, and rise nearly perpendicularly above the surface of the Sun. Their dimensions may be given as: thickness, 5000 to 10,000 km; height, 25,000 to 100,000 km; average length, 200,000 km. Exceptional features have been recorded occasionally, as in 1946, when a filament appeared at a height of 100,000 km and reached a length of about 2,000,000 km. Filaments vary in intensity; when very dark, they appear as feeble prominences, while when they are of the same luminosity as the chromosphere they lack contrast and are visible only at the edges of the Sun as prominences of great intensity. One characteristic of these filament-prominences is that they are not attached to the chromosphere over their whole length, but only at certain points, so that they resemble a line of trees with interlaced branches. In fact the features assume many forms, so that it is difficult to give a general description of them.

When a filament becomes a prominence, the complete structure appears as a number of interlaced branches or vortices with appreciable line-of-sight velocity. The luminous material which makes up the filaments may spout rapidly from the chromosphere, or may be formed in the upper parts

of the prominence at a great height above the chromosphere. In either case it is possible to observe currents in the material, falling in majestic curves down to one or more of the centres of attraction provided by sunspots or the zones surrounding them. Ring-like structures are also common; luminous material is seen as the top of a ring which falls away on either side toward the chromosphere, to which it appears to be attracted. Usually, small filaments arise from inside a group of sunspots; during a period of one or two solar rotations, a filament will move to a higher latitude and increase in size. It may be said that filaments which last for at least one rotation are formed after the sunspot maximum is past; moreover, they are orientated along the sun-meridians. During their movement toward the poles, and because of the decrease in velocity of the Sun's rotation from the equator to the poles, the filaments will move to a position in which they extend along the parallels, finally reaching this orientation towards latitude 45°. As this process takes place, the filaments increase in size; this lasts for about 3 rotations, by which time the sunspots originally associated with it have disappeared. Filaments do occur also outside the sunspot zones, but are always confined to zones occupied by flocculi. In general, however, they originate in spot-groups.

Observations made at Meudon show that the lifetime of filaments ranges from a few months to a year, an average value being 1 to 3 rotations. At any moment a filament may disintegrate and disappear, or else be swallowed into the solar surface, or, alternatively, and more frequently, break away from it. Before finally disappearing, filaments of substantial size exhibit currents with velocities up to 100 km/sec, and also changes in intensity in different areas. Often they reappear in the same position and in the same form, an effect which may be due to changes in contrast against the background of the chromosphere.

Filaments also appear in the polar zones, and probably derive from those at the equator, which migrate to high latitudes and follow the general circulatory motion toward the poles of the solar atmosphere. Such polar filaments are aligned parallel to the equator, and at times form a continuous band around the two polar zones. This occurs more frequently in years following minimum sunspot activity, as the filaments of the new cycle start their migration toward the poles from higher latitudes, and so are able to reach further. For example, a filament originating at latitude 30° may move as far as 70° to 80°, whereas one forming at 15° reaches no further than 50°. Most of the filaments disappear after two or three solar rotations, before reaching as far as the polar zones; but it is possible for them to reappear in the same place and form as when they disappeared, continuing their migration as though uninterrupted. This migration toward the poles – from which it has been possible to show that the velocity of individual filaments decreases with increasing latitude – suggests not as a mass motion of the filaments, but rather a shift of the zone of excitation. In general, a filament moves toward the pole by gradually disintegrating at the lower end, with a corresponding growth at the upper end.

The ascending and descending motions of eruptive prominences have been closely studied, first by direct visual methods and later by spectroheliograms taken in calcium or hydrogen light or with a Lyot filter. More recently still, cinematography has been employed, which has given us extra information about the forces involved in the motions of eruptive prominences. At the beginning, the ascending velocity is small, but it increases with altitude, until finally the matter making up the prominence shoots out into space with a velocity of the order of some hundreds of kilometres per second. The greatest velocity so far observed has been about 730 km/sec, which is approximately 10 km greater than the escape velocity

from the Sun. The final phase takes place in a few hours, while quiescent prominences – from which, as has been noted, the explosions begin – have lasted for several months. The velocity of ascent does not increase with altitude, but seems to remain constant to a certain height, after which it increases to a value two or three times greater than that at the beginning. This may be due to the fact that observations have not been carried out continuously. The use of cinematography may show that the increase is more regular. From observations made at the high-altitude observatory at Climax (Colorado), using a coronagraph, parabolic curves on the time–distance graph may be traced. The average accelerations have been determined in many 'knots', i.e. well-defined condensations which appear in the prominences; their trajectories are in accord with calculations made by J. Evans, based on studies of an electromagnetic field. Force-fields for knots following such trajectories are nearly constant in time up to the point where the prominence itself is of stable form, but the fields change as the shape of the prominence changes. During periods of normal activity, downward accelerations are more frequent than upward ones, but all are upward if the Sun's gravitation is taken in consideration. Prominences which change shape rapidly have higher accelerations, especially when actually altering in form, and this observational result is in accord with theoretical studies of the behaviour of charged particles moving in a magnetic field.

Observations made of a flare on 8th May 1951, at the McMath-Hulbert Observatory and at Sacramento Peak, were of special interest. The flare occurred at the limb, and developed from an eruptive prominence; it showed that there were forces involved which were more powerful, relative to gravitational forces, than could be explained by the simple laws of motion. In the case of another eruptive prominence, this time occurring in the polar regions on 7th March 1948,

observations made with the coronagraph at the Arosa Observatory indicated a number of knots moving out from the Sun, together with others which fell back into the chromosphere. The maximum altitude of the prominence was 400,000 km, and the greatest velocity 380 km/sec. Here again, the acceleration deduced from the velocity is due to a combination of the gravitational field of the Sun, and the unknown forces arising inside the prominence. The acceleration was most marked in the upper part of the trajectory, and there seemed to be a centre under the arc formed by the prominence, at a height of about 60,000 km above the chromosphere. Accelerations due to the unknown force were of the same order as those due to gravity.

As we have noted, these downward movements seem to be directed toward clearly-defined centres of attraction beneath the prominences. At times, matter is ejected which meets other material falling back, and there may also be currents of gas moving to the centre of attraction from points where no prominence has appeared. It would seem that these currents lie in the corona at a few minutes of arc from the solar limb, and that they are condensations which become visible when they have a definite direction of motion toward the centre of attraction.

Eruptive prominences found in the immediate neighbourhood of sunspots are usually small in size, compact, and probably much denser than those not directly associated with sunspots. In many cases they relate to the preceding spot of a group. Here, too, condensations may be seen forming in the corona, then swallowed into centres of attraction – in this case sunspots. The regions where condensations form may persist for a considerable time, suggesting the existence of a constant flow in the corona. To this class of eruptive prominences belong also the so-called 'surges', which are very intense but short-lived prominences rising to altitudes of 50,000 km, and

having velocities of several hundred kilometres per second. They are closely related to flares, and may indeed be flares seen at the limb of the Sun.

The usual ring-like shape of these eruptive prominences connected with sunspots suggests that not only are they caused by the magnetic fields of the spots, but also that their motion is of the electromagnetic type. The rings are simply filaments which are moving in curved trajectories, forming in the surrounding chromosphere or else falling from clouds in the corona above the sunspots. Generally they flow in to the edges of the penumbra with velocities of around 50 km/sec. Coronal condensations appear as luminous knots connected with the chromosphere by many filaments, their presence indicating that there may be formation of flares near the centre of activity. The knots are in a state of continuous agitation, with large variations in their luminosities; sometimes the whole phenomenon lasts for no more than 10 to 15 minutes. If the lifetime is longer than this, the knots are continually replaced by others. From them a coronal cloud may be formed from which is falling a luminous rain perhaps lasting above the sunspot area for several days.

The fact that the spots appear dark against the bright solar surface shows that the umbra and penumbra must be cooler than the photosphere. Direct proof of this is obtained from a comparison of spot-spectra with that of the photosphere. Hale and Adams were among the first to note that certain of the Fraunhofer lines are wider in the sunspot spectrum, and that some of the metallic lines are enhanced, while others are weak or very narrow. The spot-spectra bear some resemblance to those of K-type stars, which are somewhat cooler than the Sun. From laboratory experiments, and from the discovery of molecular bands, it was shown that the temperatures of the spots were lower than that of the photosphere.

The characteristic of stars of Type K0 is that they show

hydrogen lines which are much weaker than those of stars of Type G, and more intense than the calcium line 4227 A; then a diminution of the intensity of the continuous spectrum between $H\gamma$ and $H\varepsilon$. The most important characteristics of the sunspot spectrum are: (*a*) strengthening or weakening of a great number of lines – for some elements all the lines are strengthened, while for other elements the lines are weakened; (*b*) the presence of many lines which do not appear in the spectrum of the photosphere, many of these being grouped together in bands; (*c*) widening and, in some cases, doubling or even trebling of numerous lines, though without any strengthening of individual lines. Laboratory experiments have shown that such strengthening or weakening is due to the fact that the spot-temperature is lower than that of the photosphere. The presence of many bands confirms this. The bands are due to the following molecules: OH, NH, O_2, CH, CN, SiH, MgH, C_2, TiO, MgO, CaH, BH, ScO, AlO, ZrO, YO, MgF and SrF. The third characteristic, the doubling of the lines, was at first thought to be due to a double inversion, but is now established as being produced by the well-known Zeeman effect.

A photographic map of the spot-spectrum has been made on a large scale, using the solar tower at Mount Wilson. The behaviour of the enhanced lines is one of the most important features; all the lines appear weakened in the sunspot spectrum. Of a total of 144 lines on the Mount Wilson chart between 3900 and 7000 A, 130 show distinct weakening, while the other 14 remain unchanged. In this region, 5000 lines have been identified as due to titanium oxide, and it is found that the intensity of the bands increases with wavelength, as is apparent in the flame spectrum of titanium. Six hundred lines of CaH and about 500 lines of MgH have also been identified. From the intensity of the lines, the number of active atoms in the sunspots, the electron pressure and the temperature

may be deduced. Assuming the temperature of the photosphere to be 5740°, that of the sunspots is 4720°. From the 'curve of growth' in the titanium and iron lines, much lower temperatures (around 3800°) have however been calculated. From the same graphs it is found that the gas-pressure in the sunspots is somewhat reduced, while the electron pressure is much higher; this may explain the fact that the metallic atoms in the photosphere are ionized, whereas in the spots they are neutral. The temperature may also be measured photometrically, and yield values of from 4300° to 3700°, suggesting that the ratio of umbra to photosphere alters from sunspot to sunspot. In fact, it would seem that the smaller a spot, the less darker it appears – and that the relative differences of intensity of the bands from spot to spot shows that real temperature-differences do exist.

Another characteristic of sunspots is that their umbra may contain small bright points, resembling granules. Around the penumbra, especially in the case of a large spot, a luminous ring may be seen, having a width of the same order as that of the penumbra itself, and with a brightness some 3 per cent greater than that of the photosphere in the 4000 A region; in the visible region the contrast is much less, and the ring is difficult to see. Unlike the faculae, it becomes weaker as the spot moves toward the limb. This suggests that the phenomenon must have its origin at some depth in the photosphere.

In 1908 Hale discovered, from spectroheliograms taken in $H\alpha$ light, that groups of sunspots are surrounded by a vortex structure of hydrogen. A year later Evershed, further investigating the possibility of a circulatory movement in the spots themselves, discovered what is now called the Evershed-Abetti effect. The existence of this movement is shown by the Doppler effect when the spectrograph slit is aligned on the spots along a radius of the solar disk, or with the slit at 90° in a tangential position. In both positions of the slit, the

Doppler effect, in the case of a circulatory movement, would be seen in the Fraunhofer lines of spots away from the central meridian, between longitude 30° and 50°. By measuring the Doppler shifts of weak metallic lines, using the slit radially, Evershed proved that under such circumstances the edge of a sunspot toward the middle of the disk would give a shift toward the violet, while the edge nearest would show a shift toward the red. The observed shifts increased with the distance of the sunspots from the centre of the disk, and was interpreted as a radial outward flow of the metallic vapours in the spots; it is probably variable from spot to spot, with an average rate of 2 km/sec.

Later, C. St John found that for more intense lines such as H_3 and K_3, at a higher level in the photosphere, the Doppler shifts are reversed – that is to say, the flow is inwards to the centre of the sunspots, and has a velocity of 3 km/sec, providing a remarkable correlation between the velocity and the intensity of the lines. Assuming that the intensity of a line is inversely proportional to the altitude, the matter at the lowest level flows from the spot with a velocity which decreases with altitude. The level of zero velocity is approximately 10,000 km above the photosphere; beyond this point, the velocity begins to increase in the opposite sense.

Observations carried out at Arcetri show that as well as the variation of these movements within the indicated limits, there is also a tangential component of convective motions. By setting the slit tangentially on a sunspot, when the spot is at a certain definite distance from the central meridian, it is possible to measure shifts of an average order of 1 km/sec in the metallic lines. By plotting the radial and tangential components, it may be shown that the projection on to a plane of the motion of gases at low level is a logarithmic spiral which gives the direction of rotation of possible vortices forming in sunspots at the level concerned. These results

give a definite indication of the direction of the cyclones. For metallic vapours, it seems that the vortex rotates anticlockwise – that is to say, left to right in the northern hemisphere. Comparing this rotation with that of high-level hydrogen (as observed in spectroheliograms, or on photographs taken in

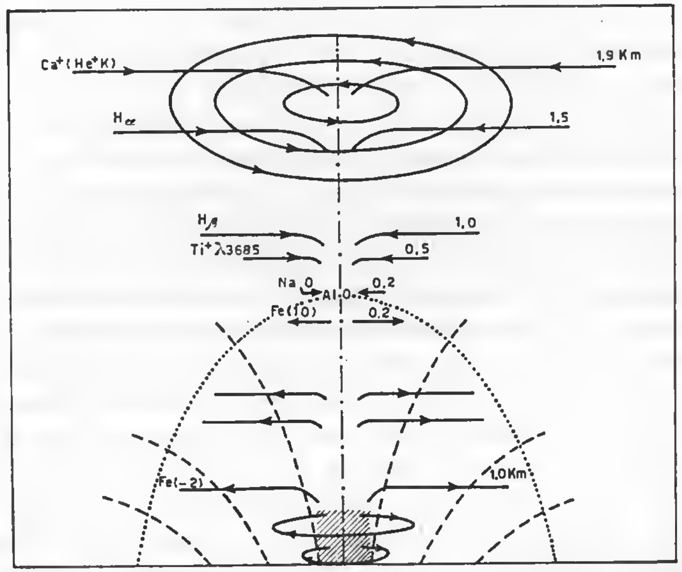


FIG. 17. Motion of gases flowing into, and from, a sunspot. The dotted curve shows approximately the region covered by the penumbra, while the lines indicate the positions of the lines of force of the magnetic field (M. Nicolet).

Hα light using a Lyot filter), it is seen that the two rotations are opposite, since that of hydrogen is clockwise.

The problem of the origin and formation of this kind of complex phenomenon remains unsolved, even when the magnetic fields of sunspots and the characteristics of the spots themselves are taken into account.

It was the existence of this vortex structure which suggested

to Hale, in 1908, that there might be a rotary motion of charged electrified particles around the sunspots, which would of course produce the magnetic fields. Following up this line of thought, Hale had the idea to build the solar towers at Mount Wilson, which were equipped with polarizers, and thus he discovered that the Fraunhofer lines in sunspot spectra revealed the Zeeman effect. Nowadays much work is being done on this problem, which is linked with that of the magnetic fields. The fields must originate in the depths of the Sun's atmosphere, and must exert an influence upon the matter in the interior layers; it is therefore possible that they are the cause of sunspots, flares, and perhaps even the high temperature of the corona, instead of being – as Hale believed – due to the spots. This leads on to theoretical considerations on the hydromagnetism, that is, on the hydrodynamics of solar matter in the presence of a magnetic field.

The Zeeman effect is visible 'longitudinally' when observations are made in a direction parallel to the lines of force in the field, and 'transversely' when the observations are made perpendicular to the force-lines. In either case, they appear in the magnetic fields of sunspots according to the orientation of the fields with respect to the surface of the Sun. If the lines flow perpendicularly to the surface when the field is near the central meridian, the effect is shown longitudinally, but is transverse when the field is close to the limb. In the former case, a Fraunhofer line is usually divided into two circularly polarized components of opposite direction, having a separation $\Delta\lambda$ with respect to a line unaffected by the field. The transverse effect shows the line divided into a symmetrical triplet in which the side components are plane-polarized, the centre one being polarized at right angles to the field. The separation is given by the formula $\Delta\lambda = CH\lambda^2$, where $C = 4{\cdot}7 \times 10^{-5}$, H is the intensity of the field in gauss, and λ is given in centimetres. Comparatively few spots show the

simple pattern called 'normal Zeeman effect'; generally the patterns shown by a line subject to a magnetic field are more complex – the 'anomalous Zeeman effect'.

Evershed at first used the green line 5250·22 A, with a shift of 4×10^{-5} A/gauss. This was followed by the systematic measurement of a number of lines, carried out at Mount Wilson, in which the Fe 6173·35 A line was used. The accuracy of measurement depends on the sizes of the sunspots, and approaches ± 50 gauss. The intensity of the magnetic field at the centre of a sunspot is directly related to the size of the spot. On the average, therefore, the intensity of the field is approximately 1800 gauss for sunspots covering 100 millionths of the solar hemisphere, rising to 2700 gauss for spots with an area of 500 millionths. At Mount Wilson, the weakest fields measurable are 100 gauss, while the strongest so far observed are of the order of 4000 gauss.

Systematic observations show that every sunspot has a magnetic field, the strength of this field varying from spot to spot; it also changes rapidly in the early and late stages of development of a spot, but remains more or less constant when the spot is at its peak. The field reaches its maximum in both area and intensity in about 12 days; then the area diminishes, but the field remains almost constant until the spot disappears. Periodical daily fluctuations of the order of approximately 250 gauss occur. At the centre of the Sun's disk, the lines of force are perpendicular to the surface; at the limb they incline at an angle of about 20°. The field intensity is greatest at the centre of the umbra, diminishing gradually and disappearing outside the penumbra.

It has been found that groups very often are composed of two greater spots, which may be separated by several degrees. The western or preceding spot (P) is generally the first to form; the following one (F) is smaller, or else is made up of various components which subsequently combine. The

magnetic characteristic of these binary groups is that the two principal members are of opposite polarity. It has been established that approximately 90 per cent of all groups are bipolar; their magnetic classification is shown by the Greek letter β. A much smaller number (about 9 per cent) are groups or simple spots having a unipolar field; these are classified as α. Finally, there are complex groups in which the field is multipolar, and shows no regularity.

In the course of the last five 11-year cycles, or since the magnetic properties of sunspots were discovered, it has been established that the polarity of the P spot of a bipolar group remains constant during the complete cycle, from minimum to maximum, but that in the following cycle the polarity is reversed. F spots are always of opposite polarity to P spots; furthermore, the polarities in the northern hemisphere are of opposite sign to those in the southern hemisphere, so that the polarity of a P spot in one hemisphere is of the same sign as that of an F spot in the other. As the 11-year cycles alternate, a complete inversion of polarity therefore takes place in the two hemispheres, so that it may be preferable to assume a 'magnetic cycle' which lasts for 22 years – as follows:

11-year Cycle	*Northern Hemisphere*		*Southern Hemisphere*	
	P	F	P	F
1933–45	N	S	S	N
1943–54	S	N	N	S

It has been calculated that the magnetic flux of an average-sized sunspot is approximately 10^{21} gauss/cm^2. By examining the images of spots as taken in Hα light, which often shows a distribution of hydrogen in bipolar groups similar to that of iron filings around a magnet, it is seen that the magnetic flux joins the P and F spots; hence this structure cannot be interpreted as a hydrodynamic vortex.

Regular observations are carried out, and the results published by (for example) the Mount Wilson Observatory and the Observatory of Potsdam. The results obtained clearly show that the variations in the intensities of spots are directly related to variations in the intensities of their magnetic fields.

The general form of the corona corresponds to the behaviour of lines of force around a magnetized sphere. This, together with the presence of magnetic fields in sunspots, led Hale to investigate the possible general magnetic field of the Sun. Working on the theory that the distribution of such a field might be similar to that of the earth, he considered that the maximum intensity of the Zeeman effect should be found at latitudes 45° north and south. In view of the weakness of the general field, the Zeeman effect would be seen only as a widening of the Fraunhofer lines. With the same polarizer as that used for sunspots, Hale and his co-workers carried out observations during the minimum of 1913, and were able to establish the presence of a general magnetic field, varying between 10 and 50 gauss according to the altitude of the lines on the photosphere.

Visual methods of measuring the broadening of the lines – difficult, because of the weakness of the field – have been superseded by photoelectric methods, which provide a better investigation and so are more reliable. These methods are based on the fact that a slight shift in the lines gives rise to a greater change in the intensity of the steeper portions of the profile. Using this principle, Horace and Harold Babcock designed an instrument with the following characteristics: a large plane grating, concentrating the light mainly in the green region of the fifth order spectrum, and giving a dispersion of 11 mm per Angström; a photoelectric detector with two slits, on which the images of the wings of the selected line fell symmetrically; two photomultiplier units and amplifier; and a lens to scan the whole of the solar disk and register the intensity and polarity of the magnetic field

of the Sun's surface on to a cathode-ray tube and camera. With this apparatus, the longitudinal Zeeman effect could be observed; it was first used by the designers during the minimum of 1954 in order to measure the weak fields, and reached an accuracy of a fraction of a gauss in the case of the Fe line 5250·22 A. The magnetograph scans the Sun's disk in a series of parallel traces, and records the polarity and intensity of the magnetic fields in the photosphere in all regions. This is shown in plate IX, the north pole being at the top, and east to the right-hand side. The spacing of the horizontal lines represents approximately 1 gauss.

It may therefore be deduced, from a study of the many magnetograms available, that the weak magnetic fields recorded indicate considerable solar activity. Moreover, they confirm the presence of a general magnetic field of the Sun, as well as the hydromagnetic turbulence of the photosphere, the origin and duration of 'centres of activity' – sunspots, flocculi, flares and filaments – and the correlation of all these with terrestrial phenomena. As the diagrams show, the areas of intense disturbance are very complex. The polarity of the general magnetic field is positive in the northern hemisphere and negative in the southern – contrary to that of the Earth's field. The intensity near the poles is of the order of $1 \sim 2$ gauss, though there are considerable differences for disturbed regions in the Sun. There are also regions of magnetic bipolarity, which are sometimes very extensive, and which follow the same laws of polarity as the spots. Magnetic fields are rarely found in heliocentric latitudes of $\pm 45°$. With regard to the extensive photospheric fields shown on the magnetograms, it may be said that the spots represent only limited local zones, where magnetic fields are more intense; this may account for the decrease in energy-flow, so producing the darkening. These observations do not show any evidence of obliquity between the magnetic and rotational

axes, as had been noted by Hale and as may be seen in the distribution of the polar rays of the corona visible at total eclipses, and the effect may perhaps be due to variations in the Sun's general field. On the other hand, the average magnetic flux at the north and south poles shows annual variations, linked with the heliocentric latitude of the Earth. These magnetic regions change considerably, both in area and in intensity, from day to day; they are transient in the sense that they disappear or lose their identity at intervals of from an hour for the smallest and weakest, up to several months for the largest. As with polar fields, the magnetic structure fluctuates greatly even in the course of half an hour.

Most of the more considerable magnetic areas are classed as bipolar (BM), though some are more complex; other areas, of limited intensity, are classed as unipolar (UM). Sunspots found in BM regions occur most often when the regions themselves are young. There are however some BM regions devoid of sunspots; some of the more extensive may cover an area greater than one-tenth that of the hemisphere. From a comparison of magnetograms and photographs taken in Ca^{II} light, a close correlation is found between regions occupied by flocculi and regions with strong bipolar or unipolar fields. It may be concluded that each BM region with an intensity greater than about 2 gauss is accompanied by calcium flocculi. No magnetic characteristics are shown on photographs taken in calcium light, though they are apparent in hydrogen light; but from the calcium pictures it is possible to deduce the intensity of the field by determining the intensity of the flocculi. The brilliant coronal arches, clearly visible during total eclipses, show that the vertical extension of the BM fields in the corona is at least of the same order as the horizontal extension, and often much greater. The UM regions are less numerous, and are of lower magnetic intensity; they may cover a large area, often with rather

uncertain limits. They may last for as long as six rotations, and attain an intensity of several gauss. So far as we know, however, they have no counterpart elsewhere.

The correspondence between these regions and magnetic storms on Earth has led to the suggestion that the UM regions may be identified with the so-called M regions (page 150), the origin of which has long been a matter for dispute. It is believed that the M regions give rise to beams of ionized particles, which reach the Earth after about two days and produce disturbances in the terrestrial magnetic field. A further proof that the M regions are identical with the UM is that they occur when the heliocentric latitude of the Earth is at its greatest ($\pm 7°$), and UM regions rarely occur below 6°. The probability of some UM regions passing near the apparent centre of the disk is greatest in March and September, during years toward the end of the 11-year cycle, when beams of particles are able to strike the Earth more easily.

By comparing magnetograms with monochromatic photographs taken in Hα, it should be possible to establish a relationship between filaments and UM regions; indeed, some filaments may form near or at the edges of magnetic regions, at times surrounding them. Others seem to appear along a line separating a BM region into two parts having opposite polarity; apparently, absorbing hydrogen accumulates along the curved lines of force of the magnetic field. Magnetic fields in the neighbourhood of a filament have an intensity of the order of 1 gauss. The slow migration of filaments toward the poles, amounting to about 1° for each rotation, can also be observed, and may be due to a gradual expansion of the BM regions as well as to their own motions.

Summing-up then, it seems likely that the existence of a general solar magnetic field with an average intensity of about 0·5 gauss is responsible for various phenomena – all of which are only to be expected in the presence of a rather weak

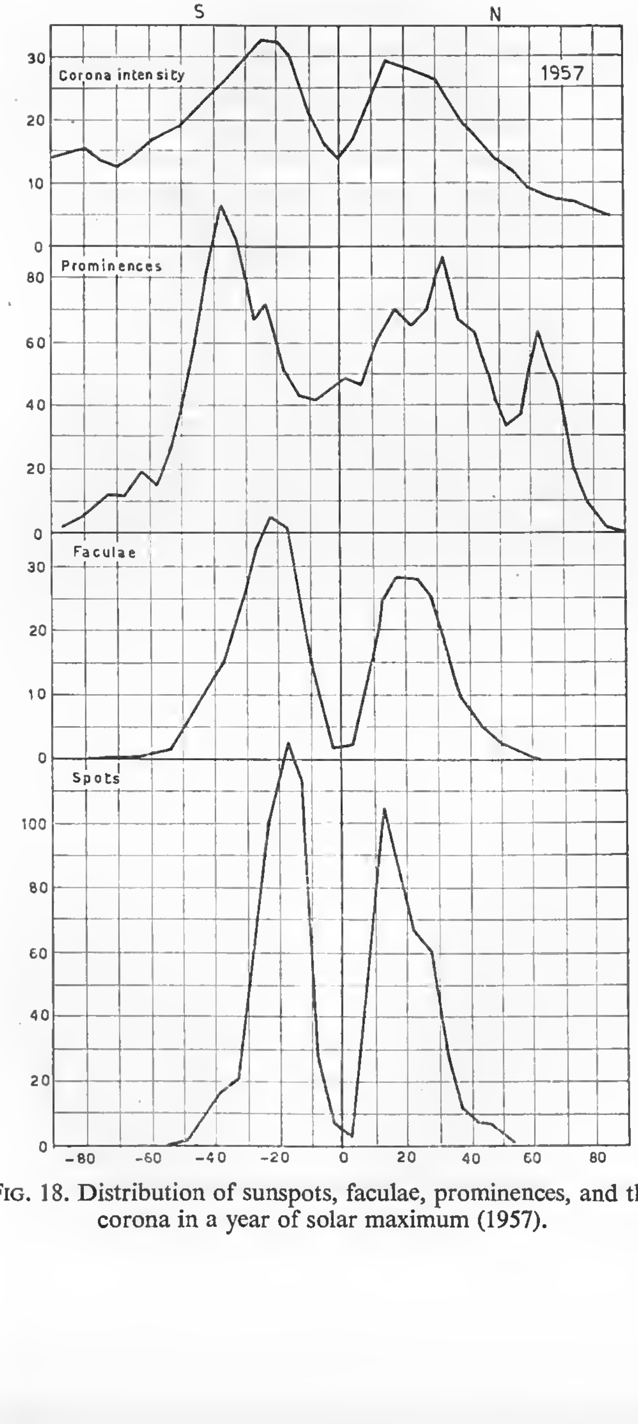


FIG. 18. Distribution of sunspots, faculae, prominences, and the corona in a year of solar maximum (1957).

field, when beams of electrically neutral ions (mainly protons) are more or less continuously emitted from all the disturbed regions on the Sun's surface. The beams travel along lines of force; they cannot be seen visually, because of the high degree of ionization, but they produce radiation which betrays itself as rays, streamers and arches in the corona.

Chapter VI

THE SUN AS A SOURCE OF RADIO WAVES

Even before the end of the nineteenth century it was suspected that the Sun was probably a source of radio waves, produced by its electromagnetic characteristics and its temperature. In 1942, following tremendous advances in radio technology, it became possible to identify radiation on a wavelength of from 3 to 10 cm as coming from the Sun; it corresponded with radiation from a black body at a temperature of 18,000°, much higher than the 6000° of the photosphere. Generally, it has since been found that radio waves emitted by the Sun and stars reach the Earth only when not absorbed by the atmosphere, which is transparent only to wavelengths of from 1 cm to 15 m approximately. However, the rapid development of rocketry means that other regions of the electromagnetic spectrum are now becoming available for study.

During recent years, various radio telescopes of different kinds have been built. Basically a radio telescope consists of apparatus of the directional kind used in radar, usually so constructed as to enable it to be directed toward any point in space. It will be readily understood that the most suitable mounting for this purpose is that already used for optical telescopes; namely, an equatorial. The most troublesome problem experienced with radio telescopes is that small points in space cannot be located with the same precision as

in optical astronomy. The wavelengths involved are about a million times greater than those of visible light, and so the resolution of a radio telescope is much less than that of an optical instrument. To achieve resolving power equal to even a moderate visual telescope, a radio telescope would have to be extraordinarily large – so large, indeed, that it would be beyond our capabilities to build it. However, as we shall see presently, there is a solution to this problem.

The most common sort of radio telescope takes the form of a wire trellis or lattice construction in the form of a parabolic 'mirror', which brings the radio waves to a focus; they are then picked up by a dipole aerial or antenna, and recorded in a receiver. Parabolic mirrors of apertures up to 80 m have been constructed; but for wavelengths above 50 cm, antenna systems similar to those used in television have been designed and are operating successfully. With the instruments of this type, a minimum angle of about half a degree can be resolved – which is equivalent to the angular diameter of the Sun. To investigate separate details on the solar disk would, as we have said, mean using a prohibitively large instrument, and recourse must be had to interferometers, analogous to those designed by A. Michelson for optical and photographic work. In its simplest form, the interferometer consists of two antennae separated by a distance of many wavelengths, and connected to a common receiver by cables of equal length. The resulting signals from each of the antennae interfere and produce an 'interference pattern' in the radio waves which permits of resolutions of the order of fractions of a minute of arc. Many types of interferometers have been built and are currently in use, their resolving power being clearly equivalent to those which would be obtained using a single parabolic mirror several kilometres in diameter. It is important to be able to investigate the Sun's radio spectrum by making simultaneous recordings at different

frequencies. Radio spectrometers, often of interferometer type design and recording the intensity as a continuous function of time and frequency, are used to analyse the complex, rapidly-changing phenomena shown by solar radio waves.

One great difference between optical and radio observations is due to the fact that the ionized gases are transparent to light, but, depending on the degree of ionization, may be transparent to some radio frequencies and opaque to others. The result is that radio waves from the lowest levels of the Sun are blocked. With increasing height above the photosphere, the frequency also increases, and so radio observations are more or less confined to phenomena occurring in the chromosphere and corona. Another important difference is that radio waves may be generated by varying electric currents, in the same manner as the electrical phenomena taking place in our own atmosphere. Probably these radiations are produced in just the same way – by swarms of oscillating electrons in the solar atmosphere.

The varying characteristics of solar radio waves mean that the phenomena may be classified into several groups. When the Sun is quiet, near solar minimum, it sends out regular radio waves, the intensity of which depends on wavelength. The 'quiet Sun' emits in the region between 1 cm (30,000 Mc/sec) and approximately 15 m (20 Mc/sec). The intensity of the waves depends solely on the thermal agitation of the atoms for, as we have seen, the Sun is to a certain extent comparable with a black body. Many investigations have been made in connexion with this radio wave-band, and the results have shown the phenomena to be highly complex. They may be classified under four headings: (1) Components which are fundamentally thermal, (2) slowly varying components of decimetric wavelength, (3) enhanced radiation of metre wavelength, (4) isolated outbursts. Type 2 includes

the occasional increases in intensity known as 'bursts', which last for several minutes and are connected with an increase in solar activity.

The identification of a fundamentally thermal current (type 1) is complicated by the fact that associated disturbances often occur; however, the currents may be explained in terms of basic black body radiation theory. In most radio observations, the density of the total flux from the Sun is measured, taking as unity 10^{-22} watts metre^{-2} (c/sec)$^{-1}$. Again, using the principle of black body radiation, measured values are converted into the equivalent temperature, T, of the visible disk, by the relation:

$$\text{Density of flux} = 2{\cdot}09 \times 10^{-32}f^2T$$

where f is the frequency in megacycles per second. At wavelengths below about 2 cm, the whole of the radiation is due to the basic black body radiation component. At decimetric wavelengths, between 3 and 60 cm, variations in intensity due to 'slowly varying components' are closely related to sunspot area, and the basic component may be evaluated by extrapolating from zero sunspot area. Similarly, in the case of metric waves the basic component is always recognizable and it may be concluded that, between wavelengths from 1 cm and several metres, all (or nearly all) the thermal radiation comes from the chromosphere or the corona.

As will be seen from Fig. 19 there is a clear correlation between sunspot area and the slowly varying component in the decimetric waveband. The apparent temperature is that of the 'quiet Sun' plus an amount approximately proportional to the sunspot area. At these wavelengths it is possible, therefore, to separate the component of solar radiation, which changes with the sunspot area and which shows circular polarization dependent on the positions of the spots and the stage of the 11-year cycle. Moreover, observations made

during eclipses enable the emission centres to be identified, confirming the existence of the slowly varying component and also showing that it originates in the areas covered by flocculi – with or without sunspots.

The partial solar eclipse of 20th June 1955, for example, was studied in the 10 cm waveband by Japanese workers,

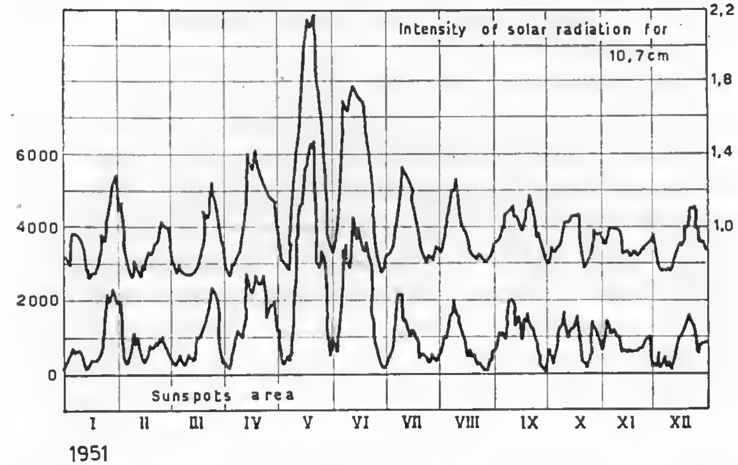


Fig. 19. Comparison between the intensity of solar radio waves of 10·7 cm wavelength, and the area of sunspots during 1951 (K. O. Kiepenheuer).

observing from three stations spread over 4° of latitude. A strong emission centre was detected, the profile of which could be clearly defined because the phase of the eclipse was not the same at all the observation sites – from one, the emission centre was covered by the Moon, while at the second station the centre was only partly hidden and at the third it was clear of the Moon's disk. The contour of the emission centre agreed well with that of Ca^{II} flocculi.

It is thought that the slowly varying component is due to thermal radiation occurring in regions of exceptionally

strong emission – that is to say, in the corona immediately above sunspots. Here, above the disturbed regions of the Sun, an exceptionally high electron density develops; 'coronal condensations' are formed above spot-groups or around prominences and often persist for longer than the spots with which they are associated. Radio observations show that the bright areas appear in regions which had been occupied by spots during the previous rotation, as well as near prominences.

Storms (enhanced radiation – type 3) are disturbances lasting for several hours or days, producing a long series of bursts or periods of increased activity in the metre waveband. The intensity may rise to millions of times the normal value, often having strong circular polarization, and occurring in large sunspots and in the corona. The intensities are not the same all along the spectrum, and differ greatly between 1 and 15 metres. It follows, therefore, that photospheric disturbances and radio waves have their source at a level high above the sunspots. If we take a frequency of about 3 m (97 Mc/sec), and assume the source to be directly above a spot, calculations given an altitude ranging between 0·3 and 1·0 times the radius of the photosphere. From observations carried out at this frequency, it may be deduced that enhanced radiation is emitted when a sunspot becomes very large; there is an undoubted connexion between the intensity of the radiation and the size of a spot. Groups made up of individual sunspots covering an area of less than 400 millionths of the solar disk rarely give rise to radio storms, though storms nearly always occur when the area is greater. The apparent temperature of the storms is of the order of 10^8 degrees, suggesting that enhanced radiation is caused by beams of charged particles. The correlation with large sunspots, together with the circular polarization, indicates that magnetic fields must also necessarily be present.

When the first observations of solar radio waves were made, it was found that whenever a flare was observed in hydrogen or calcium light, the radio waves increased markedly in intensity. At times these are so intense that they are referred to as 'outbursts'. A typical example was that of 8th March 1947, where the intensity attained 10^{13} degrees on the temperature scale – one of the highest values ever recorded. These powerful radio bursts associated with flares are received on Earth over a wide range of wavelengths, from 30 m (10 Mc/sec) to about 1 cm (30,000 Mc/sec). The shortest wavelengths come from the comparatively dense layers of the chromosphere, while the longest originate in the more rarefied layers of the outer corona. A delay always occurs between the appearance of a flare and the recording of a radio outburst, due, it would seem, to the ascent of the disturbance from the chromosphere into the corona, with the emission of longer wavelengths. The velocity of ascent is thought to be of the order of 1000 km/sec, which is also about the velocity of the swarms of particles reaching the Earth and producing phenomena such as aurorae and magnetic storms.

The 'white' flare of 23rd March 1958 (already mentioned) produced important effects over a whole range of wavelengths. The disturbance lasted for about two hours. At a wavelength of 15 cm, it was observed that the increase in radiation began at 9^h 53^m, and reached a level about four times greater than before the flare. Even after the flare subsided, the radio emission was still considerable, and coronal condensations were seen. Pulses of radiation at a wavelength of 1·3 m were recorded at 9^h, and were particularly strong between 9^h 59^m and 10^h 9^m, with a maximum intensity estimated at some 50 times greater than normal. At 3 m wavelength, the radiation discharge began 7^m after that at 1·3 m, but the intensity rose to at least 150 times the normal. This high intensity cannot be explained in terms of the thermal

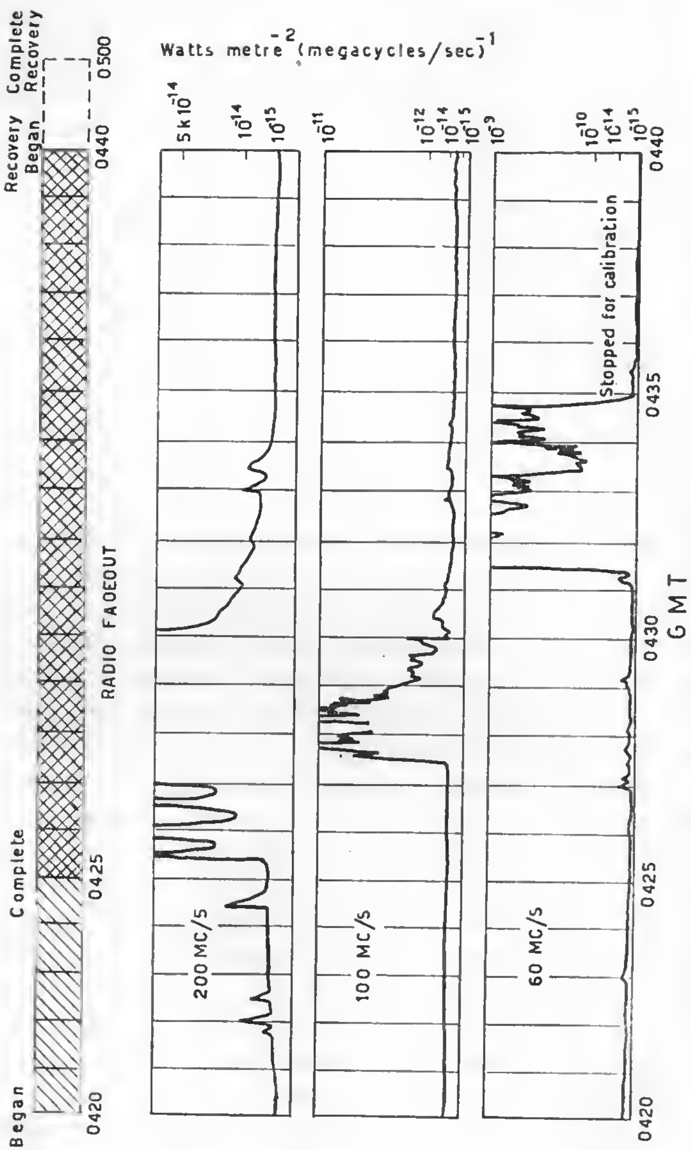


FIG. 20. Large 'outburst' of 8th March 1947 (Payne-Scott, Yabsley and Bolton).

properties of the solar material. Compared with the weak radio waves from the quiet Sun, which are caused by the random motions of electrons in the solar atmosphere, the discharge produces an additional motion superimposed on the first. Powerful sources of radio waves have been identified with the flow of material in rapid movement and in collision; something similar may well be responsible for the phenomena which we cannot so far explain with any certainty.

'Isolated' bursts – (type 4) – are so called because they appear independently of storms, and cover a wide band of frequencies extending over some tens of megacycles. They are of relatively short duration, lasting sometimes for only a few seconds. The velocity with which the disturbance rises from the lowest to the highest layers of the Sun's atmosphere is about 50,000 km/sec, or one-fifth the velocity of light. The cause of these isolated bursts is not known, and it seems that they are not associated with any phenomena visible in ordinary light.

A comparison of Mount Wilson magnetograms with radio observations made at Sydney confirms the connexion between the 'bright' radio regions and the BM regions. It would seem that the UM regions are not sources of radio waves. Babcock has explained this by suggesting that the swarms of particles accelerating outwards from UM regions are propagated radially, due to the interaction of weak and irregular magnetic fields at some distance from the Sun. Hence there is little likelihood that they will collide with clouds of ions before becoming diffused, and so they will be unable to generate strong radio waves.

The possible connexion between these bursts and the prominences has been studied by comparing cinematographs of prominences, taken at Sacramento Peak and at Climax between 1949 and 1955, with solar radio-wave records at 1·7 m (167 Mc/sec). No exact correlation has been found –

although some prominences are certainly associated with simultaneous bursts, one example being the prominence of 18th January 1955.

These preliminary results stress the importance of the solar radio observations made during the last few years. They confirm the very high temperature of the corona already found

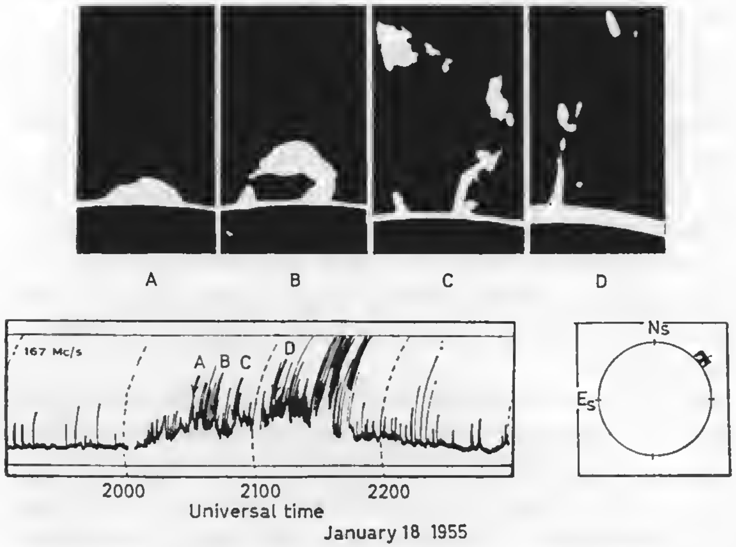


FIG. 21. Prominence of 18th January 1955, and radio-wave emission at 167 Mc/s. Average velocity 200 km/sec; maximum altitude 300,000 km approximately (J. P. Wild and H. Zirin).

by optical studies, and they provide information about the temperatures and electron densities in the upper regions of the chromosphere and inner corona. The intensity of radio waves from the corona shows that the temperature there must be a million degrees; and whilst with light-waves the outer corona is available for study only during the fleeting moments of a total eclipse, radio work shows that the corona

extends far into space, making the so-called 'radio Sun' much larger than the 'optical Sun'.

Radio waves emitted during outbursts make it possible for us to study the initial stages of the expulsion of beams of particles from the Sun's atmosphere. As the resolving power of radio telescopes is improved, the results obtained jointly by radio and optical work is bound to bring a better understanding of the distribution of electron densities and temperatures across the solar atmosphere. Those components which cannot be explained in terms of thermal radiation must be due to a different radiation mechanism, and come from sources of energy which depend on the physical conditions prevailing in the Sun.

Data regarding solar noise may be summarized as follows:

			Flux (10^{-22} watt $m^{-2}(c/sec)^{-1}$)		
λ (cm)	*ν (Mc/sec)*	*Temp. (°C) Quiet Sun*	*Quiet Sunspots*	*Typical Noise Storm*	*Typical Outburst*
600	50	1,100,000	0·6	40	1200
300	100				
150	200	900,000	6·0	100	200
60	500				
30	1000	230,000	35	0	30
15	2000				
6	5000	31,000	140		13
3	10000				
1·5	20000	10,000	840		
0·6	50000	6,400	3400		

Chapter VII

COSMIC RAYS AND THE SUN

Cosmic rays are recorded and studied at many observatories all over the world, for it is thought that the Sun itself forms one of the sources. For more than a decade it has been known that the Sun emits cosmic radiation for periods of a few hours at a time. These new studies may help us decide whether cosmic rays are of interstellar, stellar, or purely solar origin. At present it is believed that cosmic rays are produced by phenomena in the Sun, but no exact correlation with radio wave emission has been established. Neither has it been possible to find out from which layer (photosphere, chromosphere or corona) cosmic rays are emitted.

Cosmic rays are studied by means of ionization chambers and Geiger counters. On Earth only the secondary rays, triggered off by the primary rays, can be observed. In order to record primary rays, the apparatus must be taken up beyond the atmosphere. Primary cosmic rays may be of two types: (1) those caused by direct emission or acceleration of particles emitted by the Sun, and (2) those generated by primary cosmic rays of interstellar origin or which have been modulated by the Sun with regard to intensity. We also know that the Earth's magnetic field has an effect upon the cosmic radiation received, for observations carried out simultaneously in different geomagnetic latitudes, using various types of instruments, lead to estimates of the relative proportions of particles of different energy.

So far, little correlation has been found between visual

phenomena on the Sun and variations in cosmic radiation, yet it may be useful to cite some examples. On 28th February 1942, a flare of importance 3+ appeared over a large sunspot group; it was this which led T. Hey to the discovery that the Sun is a source of radio waves, and an increase of about 20 per cent in cosmic radiation was observed one hour after the maximum development of the flare. On the following day the intensity diminished, and then slowly increased again due to the disturbance of the Earth's magnetic field by the slow particles responsible for the magnetic storm. On the occasion of the appearance of the great flare of 25th July 1946 – one of the largest ever seen in an extended group of sunspots – a long fade-out affected radio reception on Earth, followed on the next day by a magnetic storm. Yet there was no outstanding increase in cosmic radiation at the time of maximum development of the flare. Not until a decrease in the Hα intensity took place was it possible to record an appreciable increase in cosmic radiation at the various stations; in each case the maximum intensity occurred between $1\frac{1}{2}$ and 2 hours after maximum Hα brightness.

Also interesting were the measures made at the time of the 3+ flare of 19th November 1949. The flare appeared over a group of sunspots at the high western longitude 70° and latitude 2°S. The Hα line extended to 22 A. Cosmic ray stations recorded a marked increase about half an hour after the maximum development of the flare; at sea-level the increase amounted to 43 per cent, and at 3900 metres (the Climax station) attained 180 per cent. The magnetic storm reached the Earth 26^h 4^m later. Important results were obtained from the 3+ flare of 23rd February 1956, at longitude 80°W, latitude 23°N. The main interest lay in the fact that the flare appeared at the limb of the Sun. From stations on Earth still in sunlight, an immediate ionospheric disturbance was recorded, together with a radio burst on all

wavelengths from 10 cm to 16 m. Cosmic ray intensity surpassed anything previously recorded. Stations in mean geomagnetic latitudes gave the following increases:

Neutrons	600%
Total mesons	58%
Hard mesons	38%

reaching maximum ten minutes after the greatest flare activity. Clouds of particles were accelerated in the neighbourhood of the Sun, speeding outwards with a velocity almost equal to that of light. Waldmeier confirmed emission from the corona in the 5694 A and 5445 A lines about half an hour after the appearance of the flare, suggesting that the cosmic rays were produced by coronal condensations and not by the flare itself. The magnetic storm following the flare reached the Earth 48 hours later.

From the various results, the correlation between flares and cosmic rays may be summed up as follows:

(1) With flares of considerable size (importance 3), there is an increase of cosmic radiation 1 to 2 hours after flare maximum.

(2) The energy of the charged particles from the Sun is less than $10 \sim 15$ BeV.* Their extra-terrestrial intensity is the order of 1 particle/cm^{2}sec. The total energy of such a solar explosion is something like $10^{33} \sim 10^{34}$ ergs.

(3) In all cases the amount of the effect increases greatly with the altitude of the station, and is also dependent upon geomagnetic latitude and longitude of the observer.

(4) Not all flares produce an increase of cosmic radiation.

It should also be noted that as the primary radiation consists approximately of 87 per cent protons, 12 per cent other particles and 1 per cent of stripped heavy nuclei, it is important to find out whether the solar radiation is similar in composition.

* eV = electron volt; MeV = 10^6 eV; BeV = 10^9 eV.

There is also a perceptible intensity variation of cosmic radiation in the M regions (see page 150) during the 27-day period. This is usually of the order of 5 per cent, but the amplitude varies with the 11-year cycle, and may at times increase to $20 \sim 30$ per cent. Usually there is a series of variations having a 27-day period, showing that there are certain definite sources of cosmic radiation – similar to or identical with the M regions. At times, these sources have persisted for over 9 rotations. Such variations, recorded at all stations, are due to primary radiation with energy at least $10 \sim 12$ BeV.

From data obtained by the Carnegie Institute between 1937 and 1946, using cloud chambers, it has been found that the variation of the mean diurnal values over the course of a year is greater at times of intense solar activity than when the Sun is near minimum. In an attempt to correlate solar activity and cosmic radiation, the Istituto di Fisica at the University of Bologna has been studying the correlation between sunspot areas and the peaks of cosmic ray intensity. In the diagram (fig. 22), the fully-drawn curve represents the mean sunspot areas, in arbitrary units, from 0 to 8 days after the maximum of the index of fluctuation. The sunspot areas are taken daily, and correspond to the total areas recorded at 12^h U.T. in the region extending 53° around the central meridian. About 20 peaks of fluctuation occurred in the period from January to September 1958. A clearly-defined maximum may be seen between $-3{\cdot}5$ and $-4{\cdot}5$, or 3·5 to 4·5 days after the passage of a sunspot group across the central meridian, the group probably caused a cosmic ray storm. The dotted curve in the diagram represents the flares in the active regions, for the same maxima of the index of fluctuation during the same sunspot period. From this we may correlate the flares with

the cosmic rays, much as is done for sunspots. In order to evaluate this index of activity, the total number of flares of magnitude 1 to 3+ is counted in each active region, using international observations, and is indicated on the graph in arbitrary units. The shape of the curve with regard to the flare-frequency agrees well with the sunspot results.

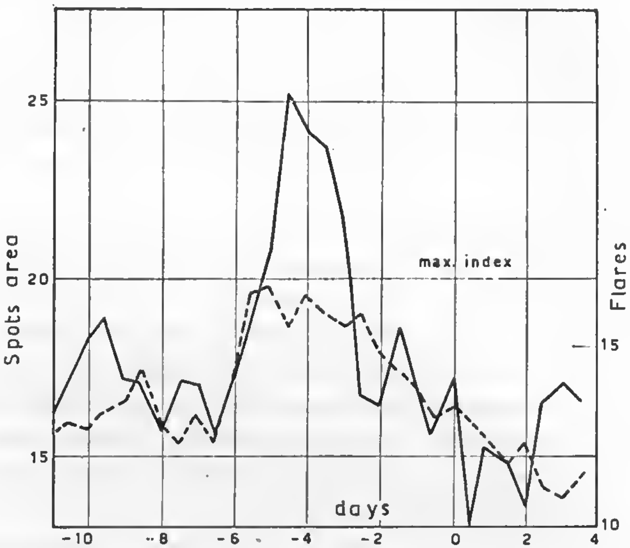


FIG. 22. Average motion of area of sunspots (solid line) and flare activity (broken line) in regions around the central meridian, from 2 days before to 4 days after maximum index of fluctuation of cosmic rays (Istituto di Fisica, University of Bologna).

Observations made at the Department of Terrestrial Magnetism, at Washington, have provided evidence of a close association between the annual cosmic-ray intensities and the numbers of sunspots; the former decrease when the latter increase. These observations covered the two cycles between 1937 and 1957, when, as we have seen, the Sun was exceptionally active. The diagram (fig. 23) shows the annual mean

of the relative number of sunspots and the cosmic-ray intensities as recorded, during the same period, at stations in Huancayo in Peru and Cheltenham (Fredericksburg) in the eastern United States. It may be seen that the years of

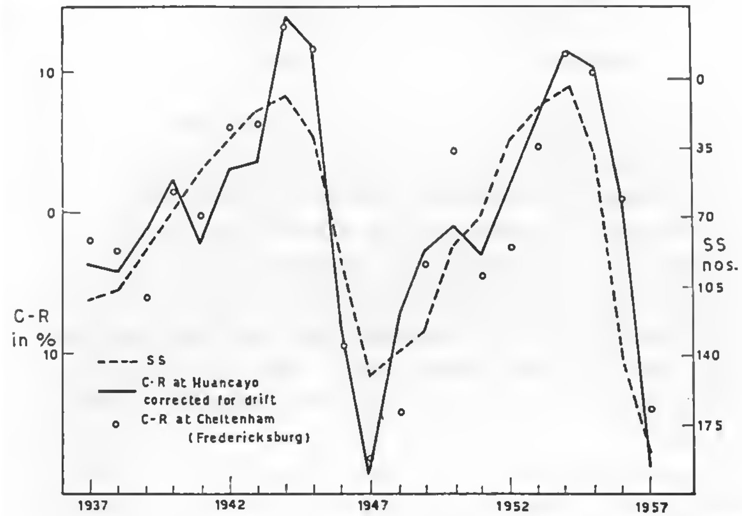


FIG. 23. The annual mean of the relative number of sunspots and the cosmic-ray intensities, as recorded during the same period at Huancayo, Peru, and Cheltenham (Fredericksburg), U.S.A.

maximum cosmic-ray intensity coincide with minimum sunspot activity. Moreover, the cosmic-ray minima in 1947 and 1957 were lower than in 1937, while the sunspot numbers were greater in 1947 and 1957 than in 1937. Decreases in cosmic-ray intensity between 1955 and 1957 followed about a year after a marked increase in the number of sunspots.

Chapter VIII

SOLAR METEOROLOGY

From what has been said, it is clear that great importance lies in the keeping of a constant watch on solar phenomena. This is possible only with the help of a vast international organization. This organization may be said to have begun in 1869, in the 'Memorie della Società degli Spettroscopisti Italiani', and has since been expanded by the International Astronomical Union. During the International Geophysical Year (1957–8) observations and studies of what is termed 'solar meteorology' were greatly increased. Now, thanks to the work of the many observatories all over the world, the Sun is watched for 24 hours a day. There are many publications dealing with solar phenomena, a few of which should be mentioned here.

Under the auspices of the International Astronomical Union, a regular *Quarterly Bulletin on Solar Activity* is published by the Federal Observatory at Zürich. It contains (1) the relative sunspot numbers, together with areas; (2) flares observed by means of spectroheliographs, or Lyot filters, together with their periods of visibility and maximum intensity, heliographic co-ordinates, magnitude on the scale of 1 to 3+, and the observation times as plotted on a daily graph covering the full 24 hours; (3) intensity of the corona in monochromatic light (in the 5303, 6374 and 6702 A lines) as recorded at the high-altitude stations at Arosa, the Pic du Midi, Climax, Kanzelhöhe, Wendelstein, Mount Norikura and Sacramento Peak; and (4) solar radio emission, as

recorded by ten stations scattered around the Earth. The daily tabulated data include the flux density expressed in units of 10^{-22} watts m^{-2} $(c/sec)^{-1}$. Variations in polarization on a scale of 0 to 3 are given, and outstanding events recorded by radio methods are shown on diagrams. Lastly, activity revealed by the spectral classification and different types of bursts are indicated, with a diagram showing the positions of the active regions. The Zürich Observatory also publishes regularly the *Astronomische Mitteilungen*, containing yearly details of the Sun's activity; the relative sunspot numbers (Wolf's numbers) obtained from observations made all over the world; faculae and their distribution; prominences and the intensity of the coronal line at 5303 A; solar radio-emission intensity at $\lambda = 10{\cdot}7$ cm as recorded at Zürich. Another annual publication is the *Heliographische Karten der Photosphäre*, which gives diagrams of the positions and development of sunspots and faculae during each solar rotation.

The Fraunhofer Institute at Freiburg-im-Breisgau, and the Observatories of Meudon and Tokyo, also publish daily charts of solar phenomena. One of the Fraunhofer Institute charts is given in fig. 24. It shows: (1) sunspot groups classified according to the Zürich scale, represented by circles of different sizes – small for types A, B, and J, medium for C, D, G and H and large for E and F. The centres of the symbols show the precise positions of the spots at 12^h U.T., while at the sides of the groups the types and numbers of the spots are shown, e.g. E30. (2) Bright calcium flocculi, reproduced from K_3 spectroheliograms in three classes: shredded and weak (hatched), continuous (bordered), and continuous and bright (bordered and hatched). Of course, this does not include any photometric information. (3) Filaments, prominences, and 'disparitions brusques'. Filaments are shown in the positions which they occupied at 12^h U.T.; rapid changes

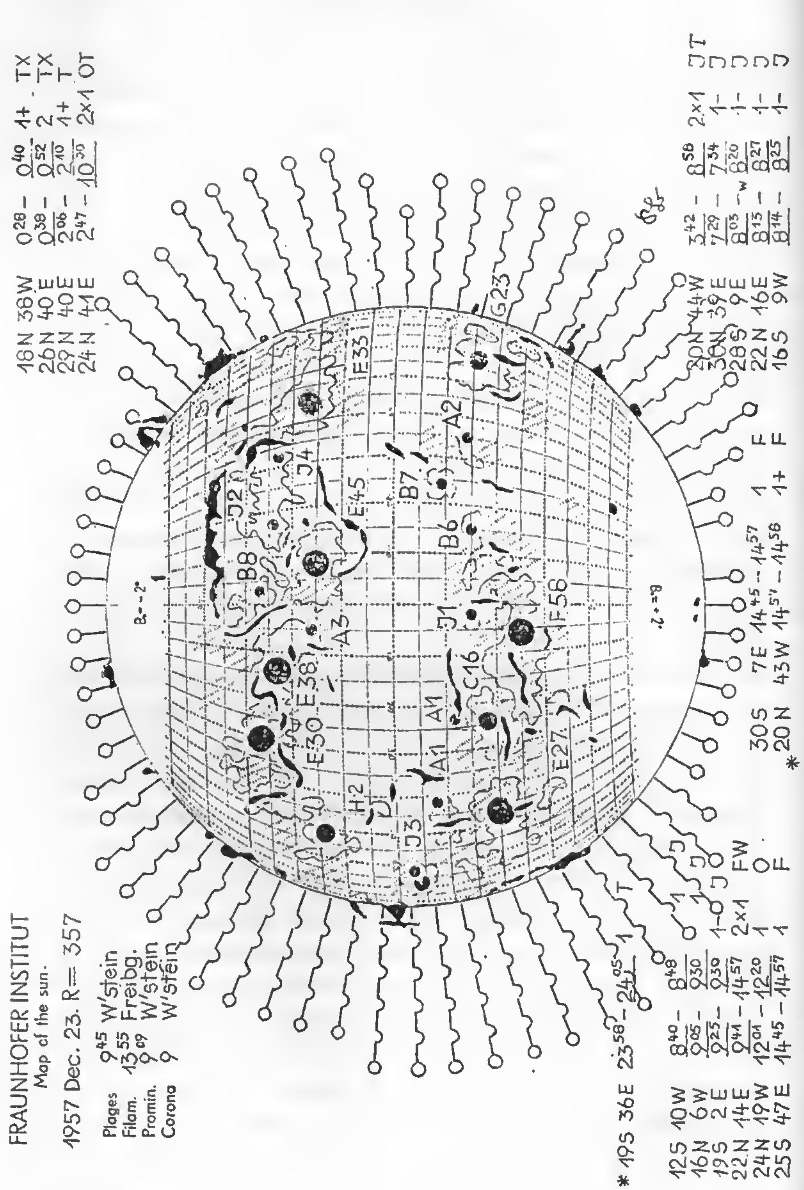


FIG. 24. Daily map of the Sun, 23rd December 1957 (K. O. Kiepenheuer, *Fraunhofer Institut*).

in filaments and prominences during 24-hour periods are also shown. 'Disparitions brusques' (DB.'s) are given where possible, with the times of their disappearance. (4) The brightness of the corona, at the Sun's limb, in the 5303 A line, referred to the brightness of the Sun itself:

1	11 to 30 $\times 10^{-6}$
2	31 ,, 55 ,,
3	56 ,, 85 ,,
4	86 ,, 120 ,,
5	$>$120 ,,

(5) Flares are shown by their heliographic co-ordinates, and with the times of their occurrence (in U.T.). Those underlined indicate the beginning and end of the flare; those not underlined indicate the starting and finishing times of the observation.

As is clear from the diagram, the Sun's disk was considerably disturbed on 23rd December 1957, and the relative sunspot number was exceptionally high.

Chapter IX

THE INTERIOR OF THE SUN AND THE SOURCE OF SOLAR ENERGY

Spectral analysis provides the means of carrying out qualitative and quantitative investigations of the Sun's surface layers; but, as has been shown, such methods can penetrate to only a very slight depth in comparison with the solar radius. Below these upper layers, no direct studies are possible. However, we do know the total mass and volume of the Sun, as well as other physical properties, such as the amount of energy which it emits. The Sun may, in fact, be compared with a heat engine having certain characteristics, and with reasonable stability, at least judged by our normal standards, and it is, presumably, in equilibrium.

As the Sun is made up entirely of gas, theoretical models of it and other stars may be drawn up – based on mathematical studies of gaseous spheres carried out by men such as Emden, Eddington, Strömgren and Chandrasekhar. Plausible theories have also been put forward to explain the origin and source of the vast amounts of energy sent out by all stars, including the Sun.

Hydrogen, helium and the monochromatic gases generally behave at high temperatures as approximately perfect gases, so that if the temperature is increased, the volume being kept constant, there is a proportional increase in pressure;

also if the volume is reduced, the density increases. Towards the centre, the weight of the overlying solar matter increases, and must be balanced by an equal force exerted from inside – namely, the outward pressure. To provide conditions of equilibrium therefore, the pressure, density and temperature increase steadily from the photosphere towards the Sun's centre. If the gas is regarded as perfect, the fundamental equations for gaseous spheres will provide the pressure, density and temperature at any distance r from the centre of the Sun, and hence at the centre itself. However, an important point must be borne in mind here: there is an immense energy-flow outward from the interior of the Sun, due to the high temperatures prevailing in the central regions. We must also take radiation-pressure into account. Indeed, radiation-pressure, combining with the gaseous elasticity in opposition to the weight of the overlying material, must play an important part in preserving the equilibrium of a star. The theory of radiative equilibrium led Eddington to the discovery of the relationship between the mass and luminosity of a star and his theoretical work has now been amply confirmed by practical observation. The model of the Sun's interior shows that while the greater part of the inner regions are in a state of radiative equilibrium, there is an outer zone which must be in convective equilibrium – except in the vicinity of the photosphere, where the transfer of energy is again due to radiation. Deep inside the Sun, radiation is produced by X-rays and by ultra-violet light. Both of these are very effective in driving out clouds of electrons from the nuclei of atoms. The atoms are left stripped, or practically stripped, and the electrons are free to wander; for this reason the matter in the Sun's interior behaves as a gas, although its density is greater than that of water. From this model of the Sun in radiative equilibrium, the following data have been obtained: mass $1{\cdot}98 \times 10^{33}$ g, radius $6{\cdot}95 \times 10^{10}$ cm. The

central temperature is 15,000,000°, and the central density about 100 g/cm^3.

The total energy emitted by the Sun can be estimated by measures of the amount of energy reaching the Earth. Each square metre of the Earth's surface receives energy equivalent to about one kilowatt. An equivalent quantity of energy is emitted for every square metre of the surface of a sphere having a radius equal to the distance from the Earth to the Sun – a sphere which has, therefore, a radius of approximately 150,000,000 km. There can be no doubt that this radiation from the Sun has been more or less constant for many millions of years, and in the past many suggestions were made to account for the long-continued production of so great a quantity of energy.

The basic process is now known to be the transmutation of elements – only recently carried out artificially on Earth, but occurring naturally inside the Sun. In such a process, a small fraction of the material of the atomic nucleus is transformed into energy. According to the theory of relativity, every change in the energy of a body results in a change in its mass.* Hence, a loss of mass corresponds to the release of energy. This occurs when hydrogen is changed into other elements, because the mass of the hydrogen nucleus is slightly too high to act as a fundamental unit from which to build up the nuclei of other atoms. For instance, suppose that it were possible to take half a dozen hydrogen nuclei to make the nucleus of a heavier element; then it would be found that the new nucleus was not quite so massive as the six original hydrogen nuclei. The excess mass would be liberated, during the building-up process, in the form of energy.

* Mass and energy are connected by the well-known Einstein equation $E = mc^2$, where c denotes the velocity of light *in vacuo*. When a gramme of hydrogen is transformed into helium, 0·007 g is converted into energy. If m is expressed in grammes and E in ergs, then the energy produced is equivalent to $0{\cdot}007 \times 9 \times 10^{20}$ ergs.

However, in the agglomeration of protons and electrons which go to form a heavier atom, although the quantity of energy released does not correspond exactly to the mass loss, it is this energy which keeps the stars radiating. Nuclear transmutation can therefore be compared with a chemical reaction: neutrons and protons represent the chemical elements, while the nuclei are equivalent to compounds, transmutation being an exchange of neutrons and protons between two nuclei. This may occur either by simple capture, when two nuclei come into contact and combine, or by a reaction in which neutrons and protons do not combine to form a single new nucleus, but distribute themselves between two existing nuclei.

An example of simple capture is that of the lithium nucleus, which may combine with a proton to produce beryllium – the excess energy being given out as a γ-ray. On the other hand, it may be that the lithium nucleus will combine with a proton and two nuclei of helium (α-particles), and kinetic energy will be liberated. Here we have an example of a reaction; and reactions are generally more common than captures. Frequently, radioactive nuclei are produced – emitting β-rays, which are negatively or positively charged electrons. Examples of radioactive transformation are the isotopes of carbon, which may be changed into boron and a positive β-particle, or else to nitrogen and a negative β-particle.

In the terrestrial laboratories, the problem of the transmutation of elements has been studied by accelerating particles electrically at high voltages, so that they acquire great kinetic energy. Under such conditions it is possible that the proton may, for example, penetrate a carbon nucleus, and so cause a transmutation. But this is an uncommon occurrence; most of the protons are slowed down by collisions with other atoms, and their energy is converted into heat, so that no transmutations take place.

Inside the Sun, conditions are very different. Because of the high temperature, all the protons have high kinetic energy, and are not slowed down by collisions – since all the atoms present have equally high energies. Therefore the production of energy is much greater since it is not necessary to bombard a target nucleus with vast numbers of electrons in order to achieve a single collision. In the Sun, and in most stars, transmutation goes on all the time.

Bethe and other workers have investigated the various types of thermonuclear reactions capable of producing the immense energy generated by the stars. They have come to the conclusion that there are two basic types of process: the carbon-nitrogen cycle, and the proton-proton reaction. It is now believed that the latter, in which protons combine to form helium nuclei with the emission of energy, may be mainly responsible for the energy of the Sun, while the carbon-nitrogen cycle is the more important for highly luminous stars. Both reactions have the same final result: hydrogen is converted into helium.

In the carbon-nitrogen cycle, the carbon takes part in a sequence of events and is eventually re-formed. The process does not consume carbon (an element not abundant in the Sun), and it may, therefore, continue over a very long period. In other words, carbon acts as a catalyst for, after bombardment by a proton, it is transformed into a nitrogen isotope* (N^{13}) with a half-life of about 10 minutes, and this in turn becomes a stable carbon isotope (C^{13}) which does not disintegrate until bombarded by protons – the only possible reaction which can take place being the capture of a proton to produce N^{14}, a stable nucleus. N^{14} can then become O^{15}, with a half-life of 2 minutes; this is transformed into the stable N^{15}. Finally, this in turn disintegrates, forming a C^{12}

* The superscript here and later denotes the atom weight of the isotopes concerned.

atom and an α-particle (or helium atom), as a result of bombardment by a proton.

The proton-proton cycle seems to operate as follows. In the first reaction, one nucleus of hydrogen combines with another, producing a nucleus of deuterium (H^2) and an electron. This then combines with another hydrogen nucleus to give a nucleus of helium-3 (He^3) and a γ-ray. In the third stage, two helium-3 nuclei combine to form helium-4 and two hydrogen nuclei. In this case also, hydrogen is converted into helium plus energy. It is therefore the abundant hydrogen in the Sun and stars which provides the source for their energy; and there is so much hydrogen that radiation can go on for very long periods. By estimating the quantity of hydrogen in the Sun, we can make an estimate of its expectation of active life.

It may be asked: How will the Sun evolve in future ages? This depends, of course, upon the internal composition, and upon whether or not a convective nucleus exists at the centre. Should there be neither a convective nucleus or any interchange of matter, Strömgren suggests that the solar model will change considerably when the central regions have been exhausted of hydrogen. This is because the outer regions will then become exhausted of hydrogen in their turn and nuclear reactions will cease.

In any case, it seems that the Sun is being carried outside the main sequence of the H-R diagram, toward the giant branch. According to Gamow, solar radiation will gradually increase in the future, becoming 100 times its present value by the time that the hydrogen has been used up. The Sun's radius will at first increase and then slowly decrease, as shown in the diagram – where the brightness and radius in future ages are shown on a logarithmic scale. Obviously, in this case the temperature on the planets will become intolerable, and the rocks of the Earth's crust will reach fusion-point, while the seas will boil. When, after many millions of years more,

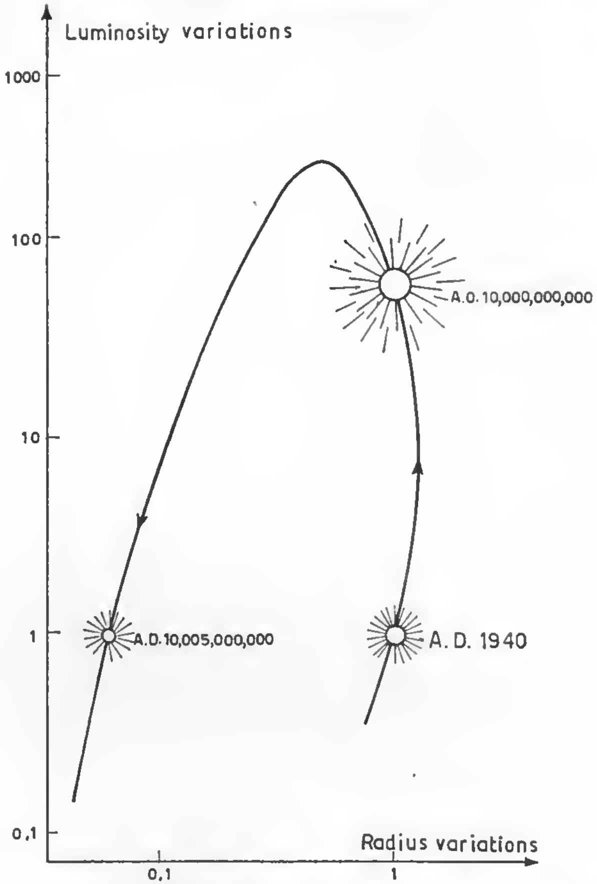


FIG. 25. Evolution of the Sun. After passing through a stage of very great luminosity, the Sun will contract rapidly, and its light will diminish (G. Gamow).

the Sun has no further reserves of subatomic energy, it will begin to contract; and as gravitational force is virtually negligible in comparison with the power of nuclear reaction, the Sun will collapse rapidly, with failing luminosity. This will take some millions of years, but at last the Sun must reach a thermal death.

Chapter X

SOLAR AND TERRESTRIAL PHENOMENA

All life on Earth is dominated by the Sun, and is in fact completely dependent upon solar radiation. Moreover, this radiation – whether normal or abnormal – has a marked effect upon events taking place on our own world. For more than a century it has been known that the Earth's magnetic field is strongly affected, and that regular or abnormal variations take place according to what is happening in the Sun. Yet the way in which these variations occur can be studied only by continuous observations both of solar phenomena and of terrestrial effects, and various types of instruments and methods are needed. Little by little, it has been established that many terrestrial phenomena are affected by the Sun; in some cases the relationship is now fairly clear, but in others we have to admit that we are still somewhat in the dark.

Continuous observations of terrestrial magnetism in its three components – horizontal, vertical and declination – show that the diurnal and seasonal variations are intimately bound up with events on the Sun. At the highest frequencies, the Sun emits radiations of different wavelengths (having the same velocity as light) and also corpuscular radiation (with a much lower velocity of from 350 to 2000 km/sec). When these various radiations – from flares or, more generally, from disturbed regions – reach the Earth, they produce characteristic disturbances in the magnetic field, which are

continuously recorded by our instruments in terms of the behaviour of the three components. In this way the so-called 'magnetic storms' are plotted.

Statistical investigations have led to the following conclusions: (1) Storms begin about $1\frac{1}{2}$ days after the transit of the associated large sunspot across the Sun's central meridian, while the maximum intensity is recorded after 2 days. (2) There is good correlation between the presence of sunspots and geomagnetic disturbances, when the spots are of area at least 1000 millionths of the solar disk; although smaller spots do not produce similar effects. (3) A closer correlation is obtained if the comparison is limited to those spots which are accompanied by flares. When these are of exceptional intensity they are always followed by strong magnetic storms, while the more frequent but less intense flares are accompanied by an increase in geomagnetic activity. (4) Near spot-minimum, when there are few flares, geomagnetic storms still occur, and it follows that minor storms do not depend on the presence of flares.

Observations show that the corpuscular cloud is ejected from the Sun in a cone which has a semi-angle of approximately 45°. Only with flares of magnitude 3 or 3+ is the whole of the cone sufficiently intense to produce geomagnetic storms. Although large spots may last for several rotations of the Sun, the magnetic storms which they produce do not recur in a 27-day rotation period. However this is consistent with the fact that flare activity associated with a sunspot lasts for less than one rotation, and that only large flares are important in the production of major magnetic storms. With lesser storms there is a definite 27-day recurrence, since their origin lies in the centres of solar activity known as 'M regions'. It is reasonable to suppose that the M region centres of activity are made up of a complex of filaments, with condensation into coronal streamers. Now we find that a filament-area develops

near the central meridian of the Sun from 3 to 5 days before an M disturbance reaches the Earth; this suggests that the filaments are themselves sources of corpuscular radiation, and that the magnetic disturbances on Earth produced by the M regions are propagated with a velocity of from 350 to 600 km/sec. It will be recalled that filament-prominences are almost always surrounded by concentric arches of condensa-

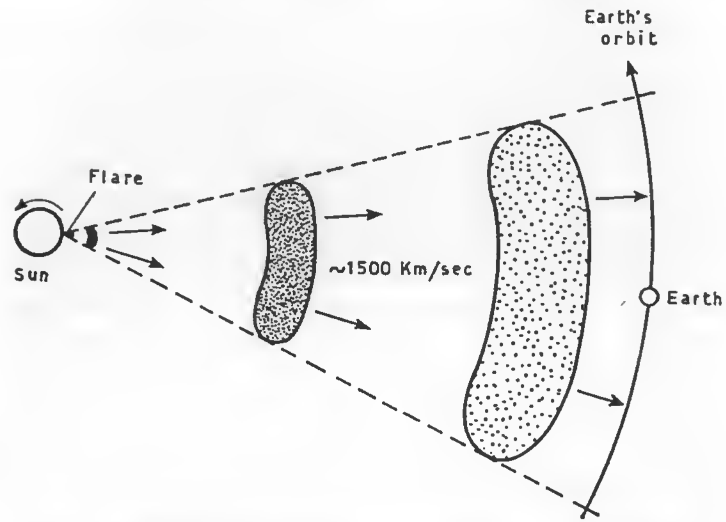


FIG. 26. Emission of particles from a flare (K. O. Kiepenheuer).

tion of varying brightness, interspersed with dark spaces – as has been shown by photographs taken during total eclipses. Frequently these great domed shells extend into the outer corona, ending in long coronal streamers. Therefore it is at least possible that filament-prominences and coronal condensations are responsible for the M regions – a theory which has been further supported by the persistence of the 27-day variation in geomagnetic activity. The corpuscular beams may be considered as extending in the manner of filaments,

and rotating with the Sun. From some eclipse photographs, it would seem that coronal streamers are three-dimensional shells consisting of extended filaments.

The discovery of the solar corpuscular radiation destroys the belief that sunspots (which, as has been noted, are gigantic magnets) are directly responsible for the Earth's magnetic disturbances. Instead, it is possible that the Earth's external magnetic field, so far measured only at low levels, is disturbed by electric currents which flow round the globe. If so, a magnetic storm will naturally be expected after the Sun has emitted a beam of corpuscles moving at a velocity of about 1500 km/sec. The width of the beam, small in relation to the diameter of the Sun, will increase during its journey to the Earth. As it approaches, it will enter the Earth's magnetic field, inducing an electromagnetic current in the beam, the beam itself being ionized, and therefore consisting solely of protons and electrons. Consequently the beam will be arrested by the force exerted by the geomagnetic field upon the induced current, and may be stopped at some distance from the Earth. However, this current, in its turn, will produce another magnetic field superimposed upon that of the Earth, generating a disturbance – the three components of which may be recorded by our instruments (fig. 27).

The well-known polar aurorae are also produced by solar storms. They are seen after geomagnetic disturbances have taken place, and must certainly be due to the same causes. The aurorae borealis and australis have as their geometric centres the north and south magnetic poles respectively, and appear mainly in high latitudes, particularly during periods of great solar activity; in lower latitudes they are much rarer. By triangulation, using stars visible at the same time as auroral displays, it has been found that aurorae are produced high in the Earth's atmosphere, between 90 and 1000 km above the terrestrial surface.

Examination of the spectra of aurorae yields information about the nature and excitation of the gases emitting the radiation. There are some 40 emission lines, together with several bands. The emission lines are due to atoms of gases which are abundant in the upper atmosphere, particularly oxygen and nitrogen. The most intense line in the auroral spectrum is that at 5577 A, in the yellow-green; this is a forbidden line due to normal atoms of oxygen, O^{I}. There are also intense lines at 6300 A and 6364 A, also forbidden lines due to O^{I}. Identification was at first difficult because the 5577 A line is very weak in vacuum-tubes containing pure oxygen, and is moreover masked by a band due to molecular oxygen. However, if a rare gas (preferably argon) is mixed with the oxygen, the green line is considerably enhanced, probably because the inert gas suppresses all the oxygen lines except those which, such as the green line, are of low excitation. The other forbidden or permitted emission lines are due to O^{I}, singly ionized oxygen, O^{II}, doubly ionized, O^{III} normal nitrogen N^{I} and, doubly ionized, N^{II}. The groups of the most prominent bands are caused by molecules of neutral and ionized nitrogen. Spectrum of molecular oxygen is very weak, except in aurorae below 100 km, apparently because molecular oxygen is scarce at higher levels.

The Balmer lines of hydrogen are present in the auroral spectrum. In 1951 Meinel, using a spectrograph directed toward an aurora near the magnetic zenith, found that the Hα line showed a Doppler shift; moreover, the profile was markedly asymmetrical, and the violet wings indicated a proton velocity of at least 3300 km/sec. Spectra obtained from the magnetic horizon showed lines widened, but no shift. This discovery provided good confirmation that aurorae, like geomagnetic storms, must be due to corpuscular beams from the Sun; from the observations it could be inferred that the beams producing the aurorae were accelerated

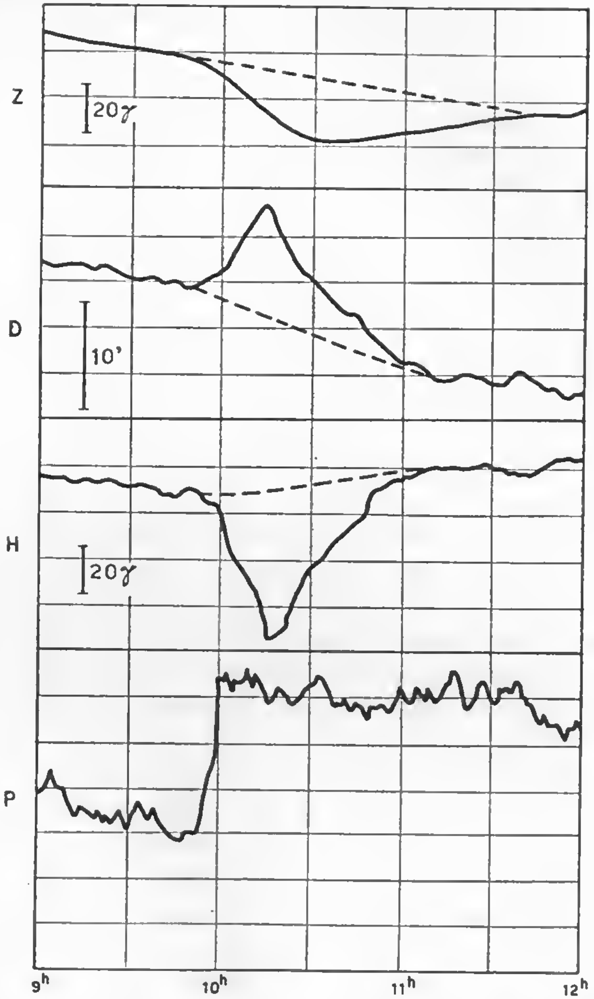


FIG. 27. Behaviour of a magnetic storm; vertical component of intensity Z, declination D, and horizontal intensity H, at Regensberg (Switzerland); and (P) the atmospherics record at Zürich (M. Waldmeier).

when they neared the Earth, and so entered the atmosphere with a velocity greater than the average velocity maintained during their journey from the Sun.

Størmer and others have worked out theories from which it is possible to calculate the trajectories of the corpuscular beams. As the beams approach the Earth and come under the influence of the terrestrial magnetic field, they bunch together around the magnetic poles, and collide with atoms in the ionosphere; this is in accord with what would be expected. The shortest wavelength which can be reflected from the ionosphere, the so-called 'frequency limit', depends directly on the number of electrons to be found in the unity volume of the ionosphere. Today, this frequency limit is being continuously recorded at many stations all over the world, and it has been found that its behaviour exactly follows the changes in solar activity. The state of the ionosphere may therefore be predicted simply by observing the Sun, and it is possible to decide the most favourable frequencies for transmissions of different wavelengths.

In 1930, attention was drawn to the fact that short-wave radio signals may fade out, partially or completely, returning to normal after a few minutes – and moreover without any apparent reason. This was observed in the sunward hemisphere of the Earth, and was accompanied by magnetic disturbances. It is known as the Mögel-Dellinger effect, after the two workers who first noticed and studied it. Again we find that it is associated with flares on the Sun because flares emit intense radiation at high frequency. The intense high-frequency radiation passes through the highest E and F layers of the ionosphere without hindrance, but is much more affected by the D layer, where the number of atoms per unit volume is greater, so that these atoms collide with the free electrons – thus weakening the radio waves. When, therefore, radiation from flares (travelling at the speed of light) reaches

the D layer, it becomes denser, and to a greater or lesser degree absorbs the terrestrial radio waves, thereby producing fadeouts in those regions of the Earth which are in sunlight.

A typical case was that of the famous flare of 23rd March 1958, which has previously been mentioned in another connection (pages 95 and 127). The normal recording of terrestrial magnetism at Regensberg, in Switzerland, showed a typical disturbance due to solar activity. It began at $10^h\ 0^m$ U.T., and reached its maximum in horizontal intensity and in declination at $10^h\ 15^m$, ending by $11^h\ 30^m$. Maximum disturbance in declination reached $-10'$; horizontal intensity* $-56\ \gamma$, and vertical intensity $-18\ \gamma$. On a frequency of 27 kc/s, the amount of interference rose rapidly to double the normal value by $10^h\ 0^m$. The Mögel-Dellinger effect was verified at considerable intensity from $9^h\ 57^m$ to $15^h\ 30^m$. All European short-wave communication was interrupted, though wavelengths of around 4 km were unaffected during the period of visibility of the flare. Considerable geomagnetic and ionospheric disturbances, very probably due to the flare, were apparent on 25th and 26th March (fig. 27).

A problem which has been much discussed and studied is that of the possible variations – past, present and future – caused by the influence of solar energy upon conditions of life on the Earth. As is well known, these conditions have changed greatly over hundreds of millions of years, but the reasons for the changes may be highly complex. If we could detect alterations in the solar constant over short or long periods of time, we might attribute variations in climate to changes in the Sun itself, but no conclusive results have been obtained, from the measures of the solar constant obtained from observation stations all over the globe at various altitudes. This is probably because the measures carried out

* In geomagnetism, the unit $\gamma = 10^{-5}$ gauss; declination is expressed in degrees and minutes of arc.

on the Earth's surface are affected by disturbances in the troposphere, and any possible changes in the solar constant are masked by inevitable errors in observation. It may be hoped that rocket research, either by orbital vehicles or space-probes, will give some positive information about the suspected variations in the solar constant before many years have passed.

In any case, there is enough evidence to establish that it should exist as a correlation between solar and terrestrial meteorological phenomena. On Earth, there are the variations caused by the normal warming and cooling of various parts of the atmosphere, due simply to the movements of hot and cold air-masses by virtue of the Earth's rotation and axial inclination; since both these factors are important, it is easy to understand how difficult it is to link meteorological changes with solar events. All we can say is that disturbances on the Sun might possibly affect different parts of the Earth in different ways, by producing changes of temperature or pressure on humidity or rainfall, or even storms.

Some indication of the influence of changes in solar radiation upon terrestrial life is given in the growth of plants by photosynthesis. Radiations of different wavelengths can accelerate the growth, as has been demonstrated experimentally. It is found that the annual increments in the stalks of high, long-lived plants reflect changes in the Sun, particularly with regard to the 11-year cycle. As trees grow, a new layer of wood forms each year; the rings are alternately light and dark, so that the age of the tree may be estimated from the number of rings. The sizes of the rings show, moreover, whether conditions in that particular year were favourable or unfavourable for growth. In the case of the Californian sequoia (*sequoia gigantea*) and the Arizona sequoia, found where climatic conditions are stable and where humidity and rainfall are regular, the rings appear in serrated

and wider groups in any cross-section of the trunk. There are some 11 rings in each group, which is a clear case of correlation with solar activity. Moreover, there appears to be a double period of 22 years, corresponding to the polarity reversal in sunspot groups (see page 114). Some of these trees were growing several thousand years before the birth of Christ, and have very clear rings which show the growth variations as influenced by spot-maxima and minima as well as the periods of greater and lesser rainfall in the areas where the trees grow.

For example, F. Vercelli has examined the trunk of a tree which had grown between 274 B.C. and A.D. 1914, a period of 2200 years, finding clear evidence of the 11-year cycle. This is also true of trees (admittedly not so old) found in German forests and in the pinewoods at Ravenna. At periods of maximum solar activity, the rings may be two or three times larger than at minimum.

Temperature, pressure, rainfall and relative humidity are important meteorological factors in the growth of plants. All of them vary, and are different even in neighbouring regions. To understand the phenomenon fully, it is necessary to build up a comprehensive picture of the average climatic conditions over the Earth as a whole and study those factors which vary in relation to the effects of ultra-violet and corpuscular radiations reaching the Earth at different intensities, according to the seasons. Therefore, studies must be carried out for the whole range of events and over wide areas. It has been found, for example, that the average level of the great African lakes Nyasa, Victoria and Albert, as well as the Caspian Sea and other large basins, is much higher at periods of maximum solar activity than near minimum. It is evident that spot-maximum coincides with very heavy rainfall.

The flooding of the Nile also follows the solar cycle, being greater at spot-maximum. All things considered, it is reasonable then to conclude that at such times there is a higher rainfall over the whole Earth. There are also greater numbers of storms and hurricanes in tropical regions. Moreover, the general circulation of the atmosphere is more violent, so that the temperature over the globe is slightly lower than the normal average. The effects are most clearly defined in the tropics, and extend toward the poles along the principal warm ocean currents; it is less regular in medium and high latitudes. Meteorological changes are also related to geomagnetic storms, which in turn depend on the events taking place in the Sun.

Though caution is needed when referring to connections between specific conditions on Earth and activity on the Sun, it is worth noting that during the last maximum, in solar conditions so exceptional, in the United States 230 cyclones were recorded in May 1957, and the total for the year rose to 924, which was the highest on record. Moreover, in 1957 American meteorological stations registered a new rainfall record, and similar conditions prevailed in other parts of the world – in England for example, where there were many cases of violent thunderstorms.

Solar ultra-violet radiation is also important in connection with plant growth. For the most part the ultra-violet is absorbed by the layer of ozone which lies at approximately 25 km above the ground, but it is found that short wavelength radiation affects living organisms even at lower altitudes – on mountains, for instance. As has been noted, there is strong ultra-violet emission at times of violent solar storms accompanied by flares, and there is also considerable corpuscular radiation. Both of these – particularly the former – may be the direct or indirect cause of increased plant growth, as is shown by studies of very old trees which have not, presumably, been subjected to harmful influences of different kinds.

Chapter XI

THE UTILIZATION OF SOLAR ENERGY

As has been seen (page 21), the solar constant at the top of the Earth's atmosphere has a value of

$$\begin{aligned} 2{\cdot}00 \text{ cal cm}^{-2}\text{min}^{-1} &= 8{\cdot}36 \times 10^{7} \text{ erg cm}^{-2}\text{min}^{-1} \\ &= 0{\cdot}140 \text{ watt/cm}^{2} \\ &= 1{\cdot}4 \text{ kw m}^{-2} \end{aligned}$$

If there were no atmosphere over the Earth, every square metre of the surface would receive an amount of energy comparable to that given out by a small electric stove. But even at the altitude of the Jungfraujoch (3500 m above sea-level) the solar constant is reduced to 1·63, and at sea-level it falls to approximately 1·45 cal $\text{cm}^{-2}\text{min}^{-1}$.

The total energy, E, received by the Earth, assuming the radius to be 6367 km, is given by:

$$E = 1{\cdot}70 \times 10^{14} \text{ kw},$$

and every form of terrestrial life is dependent on this energy. Many attempts have been made to utilize it as a substitute for other sources of power; attempts are still going on, and with some degree of success. The problem is not a simple one, because the solar energy received on Earth is scattered and has to be concentrated if it is to be utilized; moreover differences in climatic conditions mean that there are comparatively few areas on the Earth really suitable for the purpose.

Even in the time of Archimedes it was known that the Sun's rays could be concentrated at a given point by means of spherical mirrors. In 1774 Lavoisier was one of the first to construct an apparatus consisting of a lens (1·30 m in diameter) on a movable platform, enabling the diurnal movement of the Sun to be followed. By allowing the solar rays to fall perpendicularly upon a vessel containing a 1 cm layer of water at 15° C it was calculated that the water would be raised to boiling-point in an hour or so. Many years ago Abbot, at Mount Wilson, constructed and used a small solar stove for domestic purposes. In 1953, at the instigation of UNESCO, a model of a 'solar cooker' was built under the programme for aiding under-developed areas. It consisted of a parabolic mirror mounted on a support which could be turned to face the Sun; at the focus of the mirror was a vessel in which water could be boiled by using solar radiation.

On a much larger scale, but on the same principle, a 'solar furnace' has been built in the laboratories at Mont-Louis in the western Pyrenees (1609 m above sea-level). It consists of a parabolic mirror with an aperture of 90 sq. m, made up of 3000 small curved mirrors which together produce the required curvature. Solar rays are directed on to the parabolic mirror by a reflecting surface made up of 500 small plane mirrors. When the Sun shines down from a cloudless sky, the temperature at the focus exceeds 3500° C, and the furnace is therefore particularly suitable for metallurgical operations, the production of ceramics, and for certain chemical reactions – such as the direct synthesis of oxides of nitrogen from air. The working of pure iron and of chromium, the fusion and transformation of phosphates, and, above all, the treatment of highly ultra-refractory oxides in an oxidizing medium can be satisfactorily carried out at this temperature. Larger installations of up to 100 kw are planned for the Pyrenees,

and these will be capable of treating hundreds of kilogrammes of material daily.

In the Ararat valley in Armenia, a solar installation has recently been constructed, using a series of mirrors measuring 3×5 m arranged in a circle with diameter 1 km. The mirrors are mounted on 23 trolleys, rotating on concentric rails at the periphery of the circle. As soon as the Sun rises above the horizon, photoelectric cells put the whole of the equipment in motion, so that the mirrors reflect the solar radiation on to a 40 m tower; at the top of the tower there is a water-tank, which is therefore heated. This solar power-house produces nearly 11 tons of steam per hour at a pressure of 30 atmospheres, and at a temperature of 400° C. The steam drives a turbine of 1200 kw, and the electricity generated is used in irrigating the surrounding land.

One application of solar energy which will become increasingly important is the heating and air-conditioning of dwellings. In thousands of homes in the United States, especially in the south (where there is more sunshine), heat-pumps have been installed, providing air-conditioning in summer and heating in winter. With these heat-pumps, which exploit the differences of temperature of the Carnot cycle, ambient temperature can be maintained at 20° C, that of a cold stove at less than 10° C, and the hot-water supply at 80° C – no matter what the outside temperatures may be. The most efficient systems of this kind are found in the southern States, where extremes of temperature are less, where cooling rather than heating is necessary, and the demand is therefore mainly for air-conditioning. Air, water, or a combination of both may be used as the material to be heated by sunlight for use in such pumps.

Many experiments have been carried out on using solar energy for the distillation of salt water in areas where fresh water is scarce; these experiments are still going on, notably in Cyprus, Arabia, the Sahara, Australia and California. It seems that types of solar distillation apparatus can be invaluable for the production of fresh water in arid countries where other sources of available energy are scarce, and where the salinity of the natural water is less than 3 grammes per litre. It has been proved that in the Sahara, solar distillation is more suitable than any other method, as well as being the least expensive for fixed installations, although consideration must, of course, be given to the variable nature of solar energy at different seasons. However from the experience gained in California, using shallow inclined basins, it has been found possible to produce annually about one gallon of water per day for each 14 square feet of catchment area.

Much is expected from the transformation of solar energy into electrical power. The first of several experimental processes in the United States is the 'oxyhydrogen motor', which uses only light and water. Cerium perchlorate, when dissolved in water, has the property of decomposing the water into hydrogen and oxygen without itself being consumed in the reaction; all that is needed to supply energy for this is light, particularly ultra-violet light. The liberated hydrogen and oxygen are then compressed in a cylinder, and by this means we have, in effect, a powerful internal combustion engine.

Another very promising process involves what is termed the 'photo-electric pile'. This consists of a series of layers made up of silicon which has first been highly purified, and then contaminated with extremely minute traces of arsenic and boron. The photopile generates a difference of potential between those surfaces which are exposed to the light and others which are not so exposed, and so an electric current is produced. The efficiency of the device is about 10 per cent, and photopiles of this type are being increasingly employed in telephone services and in missiles. In California, a clock

driven by solar energy has recently been made and it has a limitless 'life'. A score of about twenty solar cells located around the dial produce the necessary driving power, but during the night, the clock still continues to function, because during the day energy is stored in special batteries.

Photogalvanic cells were described by Becquerel as long ago as 1839. Such a cell consists of two electrodes immersed in an electrolyte; when light falls on one of the electrodes, electromotive force is produced. Experiments have been carried out, using various types of cells, with the object of producing a practical solar battery. Metal electrodes, some coated with inorganic compounds and others with dyes, and immersed in solutions of electrolytes, will pehaps prove to be most effective for such batteries, and it may be that an oxidizing layer on the metallic electrodes would be better than other types of coating.

The barrier-layer photocell is a solid-state device, developed originally in 1876; the light-sensitive material in this case is selenium. Nowadays, photocells are used for many purposes, such as photographic exposure meters and photoelectric 'eyes'. With direct exposure to sunlight, the efficiency is about 0·6 per cent, though an efficiency of 6 per cent has been obtained with cadmium sulphide cells. However, the silicon photoelectric cell surpasses all others in the conversion of solar radiation to electricity, and great progress is now being made in this extremely promising field.

Chlorophyll is of striking efficiency, since it is able to transform three-quarters of the solar energy received into chemical energy directly available to man. Yet another method of using solar energy could be based on the process of photosynthesis; indeed, recent experiments carried out in the United States, France and Japan show that much progress has been achieved in cultivating certain plants such as algae, so that man may ultimately be able to increase the

amount of food which can be produced on Earth. These researches aim to eliminate dependence on the seasonal cycle and the fertility of the soil, by using special methods in which – for example – water is substituted for soil, and natural changes for artificial ones. American and French workers have paid great attention to a simple freshwater plant, the chlorella. This alga is easy to cultivate, reproduces readily, is rich in sugar, proteins and vitamins, and – unlike many other plants – contains very little cellulose. The minute cells which make up chlorella are almost completely full of chlorophyllic substance, so that they may be expected to give a high yield from solar energy.

From all this work, it is easy to see that there are many ways in which solar energy can be used. Researches, both practical and theoretical, are going on all the time, and with increasingly promising results.

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GLOSSARY OF TERMS

Angström unit (A). 1 A = 10^{-8} cm.

Aphelion. The furthest distance from the sun in a planetary orbit.

Arc lines. The spectral lines observed when an element is heated between the poles of an electric arc, where the temperature is higher than in a flame.

Balmer series. A series of very intense hydrogen lines in the visible part of the spectrum and first studied in 1885 by Balmer.

Black body. An ideal substance which will absorb all radiation falling on it, and which would thus appear blacker than any actual substance when cold. It would also appear brighter, for its temperature, than any actual substance when hot.

Bolometer. An instrument for measuring the total radiant energy (including that of invisible heat rays) of a body.

Calorie. See *Gram calorie.*

Carnot cycle. The cycle of operations of an ideal heat engine of greatest possible efficiency. It begins with an expansion of gas at constant temperature, followed by an expansion without loss or gain of heat to the surrounding; then a compression of the gas at constant temperature and a subsequent compression without heat exchange, bringing the gas back to its original state at the beginning of the cycle. The cycle was first investigated by Sadi Carnot in 1824.

Continuous spectrum. A spectrum in which all visual wavelengths appear without any sudden changes of intensity.

Ecliptic. The apparent path of the sun in the sky, or the plane which contains the orbit of the earth around the sun.

Enhanced lines. Those lines which appear in a spectrum of a highly excited source of light (spark).

Excited state of atoms. An atom is said to be in an excited state when it has taken up energy and one or more of its electrons have changed position in consequence.

Flame lines. Spectral lines observed when an element is heated in a flame (see also *Arc lines* above).

Gauss. The c.g.s. unit of magnetic force (alternatively, but more rarely, called an oersted).

Gram calorie. The heat required to raise the temperature of 1 gramme of water by 1° C.

Grating. An optical surface ruled with 15,000 or more lines per inch and which splits up radiation into a spectrum.

Hard meson. See *Meson*.

Interferometer. An instrument, taking a variety of forms, which makes use of the properties of interfering light waves or radio waves for various purposes. In the laboratory it is very useful for very accurate measures of wavelength or for testing optical parts.

Ionization. An atom suffers ionization when it loses one of its electrons. Double ionization occurs when two electrons are lost. Treble ionization when three are gone, and so on.

Ionosphere. The region of the atmosphere at which the air is ionized by solar radiation.

Isophote. A line on a graph connecting points of equal brightness.

Isothermal. Occurring at constant temperature.

Isotope. An atom having the same number of outer electrons (and therefore the same chemical properties) but different atomic weight (as a result of a different number of neutrons in the nucleus).

Kinetic temperature. The temperature of a gas measured by the average kinetic energy of its constituent particles (energy due to mass of particle and its velocity and mathematically $\frac{1}{2}mv^2$).

Lyman region. The ultra-violet region of the hydrogen spectrum.

Mean free path. The average distance an atomic particle can travel before collision with another.

Meson. A particle half-way in size between an electron and a neutron. It has an existence of only a few millionths of a second and may be electrically neutral or may have a positive or a negative charge. These particles have a velocity which, if high, makes stronger their powers of penetration of atoms – they are then called *Hard Mesons*.

Microphotometer. A photometer which is built into a measuring microscope for examining detailed changes in density of the images on photographic plates.

Multiplets. Groups of related lines due to changes of position of more than one electron per atom in the atoms of a particular element.

Nodes. The two points at which one orbit crosses another which is not in the same plane. The *line of nodes* is the line joining these two points.

Orthographic projection. A projection at right-angles to the line of sight.

Parallax. A measure of a star's distance, and given by the angle subtended at the star by the Earth's mean distance from the Sun, i.e. the mean radius of the Earth's orbit.

Parameter. A quantity which is constant in the particular case considered, but which varies in different cases.

Perfect gas. A gas which behaves in such a way as to obey all the theoretical laws for gases. Hydrogen, helium, oxygen and nitrogen are close to this ideal.

Perihelion. The closest distance to the Sun in a planetary orbit.

Polariscope. An instrument for measuring the amount of polarization of radiation, that is the direction in which the crests and troughs of an electromagnetic wave lie.

Quantum theory. The theory that radiation is emitted or absorbed only in discrete amounts or *quanta*. The energy of each quantum is given by $E = h\nu$, where ν is the frequency of the radiation and
$h = 6{\cdot}62 \times 10^{-27}$ ergs per sec (Planck's constant).

Resonance lines. Lines in the spectrum of an atom or ion which require the least energy to excite them.

Secular variation. A variation with a period of enormous length.

Spark lines. Spectral lines observed when an element is heated between the terminals of a high-voltage spark gap, where the temperature is higher than in a flame or an arc.

Thermocouple. A device in which two strips of different metals are joined at each end and in which these junctions are kept at different temperatures (by one junction being exposed, for example, to radiation), and so set up a small electric current.

Troposphere. The lower sphere of the Earth's atmosphere in which the majority of weather changes occur.

INDEX

Solar Research

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Abetti

E & S